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MARCH 1962

HUMAN FACTORS IN AUTOMATIC CHECKOUT EQUIPMENT: AN ANNOTATED BIBLIOGRAPHY

Dunlap and Associates, Inc.

PREPARED FOR:
UNITED STATES AIR FORCE PROJECT RAND

The RAND Corporation
SANTA MONICA • CALIFORNIA

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PREFACE

This Memorandum is a by-product of an investigation of human factor aspects of automatic checkout equipment done by Dunlap and Associates, Inc., for RAND's Project ACE. The bibliographical material appeared to be useful in its own right; hence this Memorandum, which retains the informal style of the original compilation.

The material should be helpful to system designers and military purchasers and users of automatic checkout equipment.

Distribution follows the general pattern set by other ACE publications,* and is directed primarily at Air Force and other military agencies and industrial contractors concerned with automatic checkout equipment.

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*RM-2750, An Omnibus of Briefing Papers on Analysis of Automatic Checkout Equipment and Aids to Its Design, summarizes much of the Project's results, and incorporates a list of the Project ACE publications.

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I. INTRODUCTION

This annotated bibliography was prepared by Dunlap and Associates, Inc., under contract to The RAND Corporation. The objective of the contract was to investigate human factors aspects of automatic checkout equipment (ACE); major results are presented in a separate report (Item 24, p. 22). During the study, documents relating to ACE, maintainability, and related subjects were collected and abstracted. The compilers selected for this work those publications they deemed most pertinent to the objectives of Project ACE.

Though the literature can be classified in many different ways and some overlap among classes is inevitable, it was found that a simple five-category system was useful in organizing the documents. The five subject areas are:

1. General philosophy and review of automatic checkout methods
2. Maintainability directives and guides
3. Models of the maintenance process
4. Human performance of checkout and fault-isolation tasks
5. Specific checkout systems

The general articles on checkout philosophy have much in common. They usually assert that checkout considerations must be worked in carefully from the earliest design phases, that design for maintainability is a good thing, that some ACE installations have been disappointing, and that no across-the-board or universal checkout arrangement can fit every situation. Some papers delineate the significant variables in setting up a checkout concept (e.g., Items 10 and 13) and some predict the future of ACE.

Maintainability guides have been written for most of the R&D procurement agencies in the Department of Defense, and the tendency is toward

including a strong maintainability directive in new equipment contracts (see Item 28). Several big weapon systems have their own maintainability manuals. Typically, a guide consists of an annotated checklist of design considerations, with sections on test equipment, tools, manuals, labeling, access, work environment, and procedural factors. To make an equipment maintainable, one works through the listed details and corrects unsatisfactory features until guide recommendations have been met.

Models of the maintenance process attempt to formalize relations among a few supposedly central variables and to operate on these relations. Implications of the model can then be derived, different sets of assumptions or constraints evaluated, and so forth. Most models lean toward time definitions of model parameters and are concerned with the dependencies among reliability, maintainability, and availability.

The typical paper on human performance of maintenance tasks reports time or other scores for military technicians who were required to locate selected malfunctions. Some papers are also concerned with ancillary issues, such as the improvement of maintenance ability by aids or training, factors that make troubles easy or difficult to solve, and means by which individual performance can be predicted.

Manuals on specific ACE configurations are generally descriptive and straightforward. Very few of the ACE manuals clearly relate checkout requirements, indicating that the ACE design group became active only after weapon-system and maintenance concepts were already settled.

The abstracts vary in length from one sentence to several pages. Length per se has nothing to do with the quality or significance of an item; the abstracts were written to facilitate preparation of the main report and

in some cases, a detailed write-up seemed more useful than a brief summary statement.

The scope of the project did not permit an exhaustive bibliographic effort. The abstractors continued until they believed they had examined most of the major documents, and began to encounter obvious redundancy and sharply diminishing returns. References found after the bulk of the abstracting had been completed are listed at the end of Secs. III, IV, V, and VI.

II. GENERAL PHILOSOPHY AND REVIEW OF AUTOMATIC CHECKOUT METHODS

1. Aldrich, J. A., "Automatic Checkout Equipment: An Airline Viewpoint," paper read at SAE National Aeronautic Meeting, Los Angeles, October 10-14, 1960.

   Airline servicing of flight equipment is split into two main categories: (1) line or day-to-day maintenance, and (2) periodic overhaul. Because of the tremendous cost of the aircraft, down hours are very expensive and for this reason ACE has been considered seriously as a means of improving maintenance efficiency.

   Despite this possibility, ACE manufacturers have not communicated fully with the airlines. The airlines' management is not yet convinced that military types of checkout equipment are appropriate. In many cases the original airborne equipment has not been designed with ACE in mind, so that extensive rewiring would be necessary before ACE could be installed.

   Two recent checkout projects for the DC-8 transport are described. One is a semi-automatic "suitcase tester," designed to perform 99 distinct tests, for the automatic pilot. Another tester is being built for the main a.c. generating system. Full utilization has not been achieved in either case.

   The author believes ACE should be provided for the complex installed systems only: "It would be foolish and wasteful to try to employ such elaborate equipment for any and every unit and system on the airplane ....We have discouraged the concept of a large van or truck full of electronic equipment drawing up alongside the monster jet aircraft and plugging in a tremendous cable to a receptacle on the side of the airplane to check out the entire vehicle."

   ACE can be an effective aid when new aircraft models are being phased in; as the new systems become familiar to the maintenance crews, short cuts can be taken and "it would be natural to assume that ACE would be used somewhat less frequently."

   The "black box" system of module replacement is far too costly for the airlines. Therefore, ACE that could troubleshoot down to the submodule would be very useful. Equipment that could test several details on a single system is preferable to equipment that can accomplish gross checks on a number of systems. Equipment must be convenient to connect, easy to interpret, and manageable in terms of weight and bulk.

2. Argonne National Laboratory, Proceedings of a Symposium on Large Scale Digital Computing Machinery, November, 1953, 295 pp.

   One item of this collection is relevant to checkout. Goldstone's paper, entitled "Some Experiences in Coding and Programming with the Institute Computer," describes some techniques for rapid checking of programs. Presumably these techniques would be applicable to self-check and fault locator routines.

3. Bock, L. L., and M. Macauley, Computer System Reliability, Engineering Research Associates, 1953.

This early paper treats the problems that arise in achieving reliable digital computer operation. The techniques adopted for Univac I are described. Reliability being an unknown, the equipment was cautiously designed to include as many checks and redundancies as possible. This design philosophy yielded a high percentage of operating time compared to down time. The paper gives some statistics on operating time and reviews the design principles involved in circuit redundancy.

4. Briggs, S. J., Presentation to Second Human Engineering Work Group Meeting FBM System, Nortronics NSS Report No. 749, October, 1960, 8 pp.

Cost figures for maintainability are presented. "Air Force studies show that the direct cost of maintaining equipment runs about two dollars per year for every dollar's worth of equipment. This is only direct cost, that is, the cost of operating the various depots, field shops and flight line activities, and the cost of replacement parts. This does not include the indirect costs of training, logistics, and other indirect costs....In reality,...the true cost of maintaining a dollar's worth of military electronic equipment is probably closer to $20 than it is to $2.

"From the USAF Electronics Maintenance Conference we learn that at present, one out of eight interceptor aircraft is available for use. The other seven are 'being maintained'....For the B-52 system,...about 37.5 hours flight line maintenance time is spent per flight hour."

Three major maintainability requirements are logistic, training, and time. "Logistic requirements are reduced as component repair work is done closer to the operating equipment." Time and training requirements are closely related because "any systematic approach to time requirement reduction must include an analysis of maintenance procedures with simplification as a goal. Such an analysis will result in the elimination of irrelevant job activities, the simplification of decisions, and the inclusion of well designed job aids. All of these tend to reduce training requirements."

Nine kinds of down time are listed:

1. Fault detection time
2. Waiting time for technician
3. Fault verification time
4. Access and preparation time
5. Fault localization time
6. Waiting time for spare parts
7. Fault correction time
8. Alignment and adjustment time
9. Checkout time

"Between 60 and 80 per cent of the (total) time is spent on two of the listed items, namely, fault location and access." Ways of reducing those times are illustrated. The access problem is the simpler of the two and can be handled by improved standard connectors and fasteners. In the fault isolation problem, techniques such as self-test, error detection, and module output quality checks are useful in streamlining the work. It is recommended that a definite fault-to-resumed-operation time requirement be imposed on the system designer; a 15-minute goal was set up for the Polaris missile. Similar standards for "component-fix-time" are also expected to be useful.

5. Bright, J. R., Automation and Management, Harvard University Press, 1958, 270 pp.

In 1954, a project to study the impact of automatic data processing was begun at the Harvard Graduate School of Business Administration. This volume reports detailed results from thirteen automation programs which were carried out in American industry. Seventeen levels of mechanization are defined in such a way that "mechanization profiles" can be drawn for a manufacturing sequence. Among the many automation issues treated are expected-versus-realized advantages, installation and procurement problems, the impact on sales and work force, and organizing for automatic production.

6. Bull, W. I., "The Navy Outlook on Maintainability," in F. L. Ankenbrandt (ed.), Electronic Maintainability, Vol. 3, Reinhold, New York, 1960.

"Any discussion of maintenance must concern itself with the four fundamental elements involved: the man, the maintenance manual, the test equipment, and the repair parts." The POMSEE maintenance standard books are described; a special book for each piece of equipment shows the technician how to accomplish the required checks. Spaces are provided in the book for entering parametric values, so that a permanent performance record can be made. Standard measurements for that particular equipment item are entered at the shipyard when the equipment is assumed to be in peak condition.

Airborne and missile equipment tend to have replaceable (but repairable) modules and automatic checkout tests. "For all types of equipment in the Navy, it is quite obvious that there will be a marked increase in the use of built-in test features and automatic fault locators. For extremely complex equipments this is fast becoming essential. And of course, the need is compounded by the shortage of competent military technicians." However, "we will still have to concern ourselves with maintenance policies and depend heavily on the technician and his test equipment to keep our complex systems operable."

7. Cooper, J. I., L. V. Rigby, and W. A. Spickard, Proceedings of Shirt Sleeve Seminar on Maintainability, Northrop Corporation, Norair Report NOR-60-3201, August, 1960, 118 pp.

This document is a verbatim record of a seminar in which twenty-four human factors and design engineering specialists discussed maintainability problems. The following paragraphs indicate some of the central themes relating to test and checkout operations. The quotes should not be construed as reflecting the unanimous opinion of the participants.

There are four major maintainability problems: (1) how to design for maintainability; (2) how to determine the degree of maintainability that has been provided; (3) how to choose the right design among several alternatives; and (4) who should implement and be responsible for maintainability design. There are now several guides for the first. The second is still very much a problem. The third is an operations analysis problem that needs inputs from those who are in a position to estimate trade-offs between maintainability design features and other weapon system goals. The fourth seems to require a special maintainability group.

Reliability and maintainability are not independent. Equipment that is almost 100 per cent reliable still requires preventive maintenance, or its reliability will be degraded. Thus, even in highly reliable weapon systems, there will still be a need for good maintainability design.

The Systems Analysis and Integration Model (SAIM) (see Item 51) can be used to show the interactions between maintainability and other system elements. SAIM is a general system model in which the system is composed of (1) external determinants, which constrain the system; (2) components, which are the men, machine, and facilities; and (3) integrative elements, which bind the system components together. Another matrix, similar in appearance to SAIM, can be used to index detailed maintainability design information. This matrix has three dimensions: (1) equipment attributes (coding, connectors, controls displays, external accessibility, fasteners, etc.); (2) maintenance actions (malfunction recognition, diagnosis, servicing, adjusting, removing, replacing, repairing, rechecking); and (3) maintenance level (depot, field, bench, launch pad, flight line, inflight).

For example, the SAIM should indicate a particular interaction between a system design element and the size of an access door. The other matrix would then lead the maintainability engineer to an acceptable access door design. This matrix would not show directly the consequences to weapon system effectiveness of violating optimum design for maintainability, but it does show the system designers that a problem exists. This is a trade-off problem and maintainability engineers should not attempt to restrict the trade-offs to the human factors area.

A persistent problem is the frequent inability of the human factors specialist to specify how much and even what kind of degradation to the weapon system will follow from violating optimum maintainability design features. One approach is to consider the primary criteria of good maintainability (rapidity, ease, economy, and accuracy) and give each a qualitative weight for every item in a maintainability guide.

The intent of the matrix and scaling approach is to give the designer a simple, comprehensive, and consistent framework within which he can organize his own inputs. "And this seems to be a basic problem with maintainability today; most of the things which are done in the name of maintainability are done by the engineer on the drawing board. This is true simply because for every maintenance engineer or every human engineer, there are 50 to 1500 designers."

Thus, the primary value of interaction matrices is that they can point out maintainability problems. All of the solutions may not be known, but it is still important to identify a problem and then provide all the currently available data relevant to it. One difficulty in stating concrete solutions for any one cell defined by the three-dimensional matrix is that there are so many variables. It is difficult to provide an index of maintainability information that contains maintainability design prescriptions rather than principles. Due to interaction effects, it may not even be feasible. However, the design guides commonly used by engineers have the same limitations, e.g., the discussion on tensile strength of steel will include numbers, graphs, and diagrams, but also will say that tensile strength is affected by heat. The three-dimensional matrix on maintainability design details, though written at a cruder level of specificity, will be similar in intent; it will state principles, or even formulas where they exist, and it will point out interactions.

There is a need for a maintainability design guide for the systems analyst and design engineer that tells him when and what maintainability design considerations should be applied to the design of a weapon system. Present guides present the total body of things that ought to be done with regard to maintainability design, and merely urge the weapon system designers to accomplish them as early as possible. A system guide is needed that mates procedures used in developing a maintainable system to the actual milestones in system development. One way of approaching this is to list the decisions made in the design process that have a direct influence on maintainability.

In order to be effectively implemented, such a guide would have to be made into a military standard. Present day maintainability documents, no matter how well written, are read by only a few design personnel. It might be better (1) to have the weapon system require maintainability design in accordance with a certain guide or group of guides specially prepared for maintainability, and then (2) to have the responsibility for implementing maintainability design given to a special maintainability group rather than the general engineering group. At least the reliability issue has been successfully handled in this way.

Maintainability specialists should be concerned with the original requirements for a weapon system because these requirements evolve as design work proceeds. At first, one cannot ordinarily state clean-cut requirements, such as how much time is available for maintenance. The maintainability group can be of great assistance in setting tentative requirements and successively refining them.

An engineer does not assemble an electrical circuit to perform a given function by picking components at random and then testing to see if it does perform the function. He has a scheme in mind that presumably gives him a high probability of coming up with a circuit that will perform this function. This same kind of scheme, and this same kind of "expectation," is needed for maintainability design also.

One reason for instituting a maintainability group is that there are so few maintainability people per design engineer. A separate group is required to help introduce inputs to the designers who have no background in maintainability. Another reason for establishing a maintainability group is that the average design engineer does not use the guides available today, and there is no assurance that he would use guides even if they were better. Some central source to push maintainability implementation appears essential.

Evaluation of maintainability design appears to be unexploited. The traditional problems of criterion development can be expected: reliability of measurement, combination of partly correlated indexes, etc. A major problem is that the usual criteria are far too broad: the need is for proximal criteria, not distal. Perhaps it is going too far to try to relate the effects of a particular accessibility design to the ultimate performance of the weapon system.

8. Department of the Air Force, Maintainability Program for Weapon, Support, and Command and Control Systems, AF Regulation No. 66-29, November 22, 1960.

"This regulation states the policy, responsibility, and basic procedures for the USAF Maintainability Program for weapon, support, and command and control systems. It applies to Air Force activities engaged in research, development, testing, procurement, maintenance, and operation of new Air Force systems, subsystems, and components."

9. Fellows, J. L., Jr., The Human Factors Engineering Aspects of Maintenance, Fifth Annual U.S. Army Human Factors Engineering Conference, Redstone Arsenal, September, 1959, pp. 69-70.

"Space restrictions placed on the battlefield by the threat of atomic warfare will seriously limit the number of people we can devote to maintenance, and as a result limit the time we can spend to perform maintenance at the organizational level." (It seems reasonable that this restriction applies also to certain Air Force activities.) "This means that we must develop the state-of-the-art to meet these restrictions. We cannot tolerate any extra units, or extra people, or extra equipment to perform maintenance, which can be eliminated by adherence to the principles of human factors engineering."

The following goals should be considered in equipment design:

1. Improve accessibility for adjustment and minor repair by the operator.

2. Reduce time required to perform this adjustment and repair.

3. Reduce technical skill and manual dexterity required for adjustment and both minor and major repair.

4. Reduce number of special tools and test equipment needed in the field.

5. Reduce checkout in the forward areas to simple go/no-go checks with quick plug-in assembly replacements.

6. Design assemblies and subassemblies to permit economical throw-away of faulty items instead of costly repair.

7. Design automatic test equipment for use in rear areas for expensive assemblies that must be repaired instead of thrown away.

10. Firstman, S. I., M. Kamins, and B. J. Voosen, Automatic Checkout Equipment: Employment and Design Considerations, The RAND Corporation, Report R-358, September, 1960, 78 pp.

This report considers six design choices that arise in the development of nearly any checkout system:

1. Internal and external programming

2. Open-loop and closed-loop testing

3. Static and dynamic testing

4. Analog and digital measurement methods

5. Qualitative and quantitative testing

6. Integral and auxiliary test equipment

Alternatives are examined on the basis of cost, speed requirements, availability, flexibility, and accuracy. In none of the six issues does it appear that a particular alternative is universally favored. Trade-off relations (e.g., cost versus accuracy) are hypothesized for some of the alternative configurations.

While it appears impossible to formulate a comprehensive set of rules that can render an "automatic" evaluation of particular ACE designs,

the investigation did reveal guidelines that remain standard over a wide range of circumstances. Thus, analog systems are usually cheaper if accuracy requirements are not too stringent. Qualitative indications are often insufficient for estimating "confidence" in system state; if analog computers are employed as feedback elements, then self-test may prove difficult or expensive.

"No clear-cut preferred method emerges as a universal solution to all problems, or even to any broad class of problems, in this field. The weapon-system characteristics and support requirements; the tester's required speed, accuracy, and reliability characteristics for each function of the system; and, most important, operational considerations, all will affect the composite and will often present conflicts. Each design is likely to involve a compromise among various considerations. Rarely, if ever, will all considerations lead to the same method or unique combination of methods."

11. Folley, J. D., Jr., <u>Maintenance Job Simplification Without Automation</u>, American Institute for Research, Memorandum No. 14, September, 1959, 7 pp.

An inverse relationship is postulated between equipment complexity and the quality of maintenance. Solutions involving ACE and increased training time have not proven entirely satisfactory. Use of ACE has created new problems--maintenance of the test gear itself, increased cost, logistics, longer lag in equipment development, and increase in over-all system size.

Troubleshooting is the main problem; one possible solution entails the provision of complete instructions for the full range of troubleshooting problems to be encountered.

In 1953 Dr. Robert B. Miller made practical suggestions for the content and format of job manuals to simplify the training problem. Also in that year Miller, Folley, and Smith suggested the "half-split troubleshooting technique." Since that time, a number of studies have demonstrated that fully routine troubleshooting procedures are feasible and can be applied by unskilled persons to troubleshoot complex equipment.

The difficulty with such complete troubleshooting procedures is that they are cumbersome. Many pages and contingency prescriptions must be provided. Research is needed to establish the optimum degree of routinization for manual troubleshooting procedures. It is speculated that maximum maintenance efficiency is greatest when the procedures are near the middle between the two extremes of "no procedure, all decisions" and "all procedures, no decisions."

"1. The entire troubleshooting task need not be completely procedural. In fact, zero-decision procedures are probably more cumbersome than necessary.

2. Troubleshooting aids start with some kind of systematic check of the system, or portion of the system. Do not try to start with haphazard malfunction indications that you can think of.

3. Indications at any step in the checkout procedure or troubleshooting procedure can be dichotomized into a specified indication on the one hand, or 'anything else' on the other. This makes an easy-to-follow two-alternative choice at each step.

4. You can make any assumptions that are appropriate about the skill level of the technician and pitch your troubleshooting procedure at that level. Whether the technician be a novice or an expert, some hints regarding the procedure to follow will probably be helpful.

"Remember -- if you cannot prepare some kind of a troubleshooting procedure, or your design engineers say it is too complicated to be done, you are hiding your head in the sand with regard to the maintenance of your system. If the designers cannot tell how to troubleshoot the system, how can you realistically expect the maintenance technician to figure it out?"

12. Franks, P. E., and C. W. Furnish, Automated Maintenance: Theory, Practice, and Implications for Training, WADD Technical Report 60-412, August, 1960, 23 pp.

The automatic checkout concept may be justified insofar as it (1) reduces skilled manpower needs, or (2) serves to achieve an extremely short operational reaction time. A successful checkout system "must be multipurpose, accurate, efficient (in terms of testing time), seldom fail, and have a quick change capability while keeping costs within reasonable limits."

A developmental trend toward more "universal" testers is indicated. Thus, any checkout system can be described in terms of four basic units: (1) the instruction center or programmer; (2) the stimuli subsystem or signal generator; (3) The data summary subsystem or comparator; and (4) the self-test subsystem which monitors the checkout system itself. Within each of these four units, one can delineate more detailed functions (e.g., interrogator, timer, digitizer, etc.) that are still not specific to a given system. The performance limitations of an automatic system are likely to include intermittent failures, waveform comparisons, mechanical checkouts, and adjustment of out-of-tolerance components.

Functional tests, conducted with the equipment in its normal environment and operating state, are distinguished from marginal tests, which push system parameters to or beyond operational extremes. Marginal tests may be useful in predicting incipient failures in a large collection of

parallel, similar circuit elements, since only a few parametric excursions (e.g., heater and screen voltages) are required for checking all the components. Functional tests are most practical for subsystems that are highly variable and arranged in series.

Over-all systems checks are favored over component tests because they "include tests of internal cabling and critical matching of major subsystems." Component tests may be good for automatic troubleshooting and are "especially useful with isolated networks of passive components, cable and harness assemblies, etc."

Both static and dynamic tests may be programmed into an ACE sequence. In a static test, a program of intermittent signals is applied, and outputs are allowed to reach a steady state before comparison. The dynamic test simulates a continuous input and exercises the system under more realistic conditions. Dynamic tests are generally more difficult to instrument and evaluate, but the information gained has direct operational significance.

Closed-loop testing, though essential for engineering evaluation, is not usually satisfactory for field ACE applications since it introduces additional equipment complexity and its intrinsic self-correcting features tend to suppress cumulative performance trends. In contrast, the open-loop test is simpler, cheaper, and more directly indicative of over-all system performance. "From present experience in military field operations it is believed that the open loop, dynamic system test is the best test exercise in the sense that it most frequently provides an optimum tradeoff between cost and complexity versus system reliability. In some cases, however, a static test should be considered as it may permit considerable savings in hardware with little detriment in test quality."

What tasks should be left for the technician? These will depend on the system to be checked and the amount of information desired. An illustrative checkout system (for the A3J Naval aircraft) prescribes the following manual operations:

1. Make cable connections
2. Make initial settings in test unit
3. Use the instruction book for interpretation
4. Monitor and analyze self-test results
5. Make replacements
6. Make adjustments to prime equipment

Assuming that ACE will soon be in use and time is short to prepare for its impact, the anticipated effects of ACE on personnel skill levels, motivation, logistics, cost, system accuracy, and training are discussed.

Some of these effects are likely to be complex and subtle; e.g., automated checkout may actually raise average skill levels rather than lower them, but the requirements for extremely high skill levels may be sharply reduced. Increased emphasis on ACE in existing training courses is recommended; this will provide backup if ACE does not prove to be as reliable as anticipated.

13. Gibson, W. R., "What Price Maintainability," in F. L. Ankenbrandt (ed.), Electronic Maintainability, Vol. 3, Reinhold, New York, 1960.

"Good maintainability is a highly beneficial equipment attribute. However, the allowable expenditures of manpower and time to achieve this goal must be kept within definable limits. These expenditures must be identified, assigned a value, and evaluated with relation to the net gain to be realized from each maintainability recommendation."

A system for estimating trade-offs between maintainability costs and gains is described: When the maintainability engineer makes a recommendation, it is examined according to the resulting net change. A work sheet for recording trade-off estimates is reproduced, and sample entries are described. Many factors are recorded for each design recommendation; e.g., "customer" gains or losses, such as scheduled servicing demands and mean-time-between-failures.

14. Hirshon, S., "The Air Force Outlook on Maintainability," in F. L. Ankenbrandt (ed.), Electronic Maintainability, Vol. 3, Reinhold, New York, 1960.

"The Air Force must move forward with industry to develop the philosophy and methods for the production of more maintainable weapon systems. Again we will repeat that the establishment of maintainability in meaningful terms is necessary to establish the benchmarks for sound engineering judgments to achieve maximum weapons value. Maintainability is a major design parameter and is a measure of weapon system effectiveness. Therefore, all its significant aspects must be identified, specified, measured, and controlled to produce weapon systems which can be most economically maintained in a condition of readiness.

"We visualize completely automatic sensing devices which when coupled with built-in redundant circuits will rapidly detect the faulty unit and revert to the additional operating mode for safe operation. We visualize automatic self-calibrating and self-regulating equipment to insure constant in-tolerance operation coupled with warning devices to indicate when out-of-tolerances cannot be self-corrected. We visualize built-in marginal stressing circuits which will predict incipient failures and indicate the need for preventative maintenance. We visualize all low and medium-power and most high-power electronic circuitry handled by solid-state modules one-twentieth to one-fiftieth the size of present-day conventional units performing the same functions. Such modules because of their high density and solid-state construction, will not be

amenable to economic repair. We therefore visualize extensive use of disposal at failure maintenance rather than repair-type maintenance. The designers incorporating disposal at failure-type modules coupled with built-in fault locating devices will largely eliminate the need for highly trained technicians for repair."

15. Holahan, J., "Direction and Better Engineering Needed for Automatic Checkout," Space/Aeronautics, Vol. 34, No. 4, October, 1960, pp. 210-214.

The article states that ACE is a confused field. Part of the confusion is due to the manufacturers, "both by (their) poor engineering and by (their) grossly overstating the capabilities of their products. The sales claims of the average checkout equipment company are at least five years ahead of engineering performance." As a rejoinder, the manufacturers can claim that the military doesn't have a firm maintenance policy. A case in point, they say, is the military's wavering attitude toward throwaway modules. "If ever put into practice, it would undoubtedly simplify checkout design and, in fact, the entire maintenance problem. But...because these decisions haven't been made, checkout gear today must be designed to localize faults down to as close to the piece part as possible."

Several persistent problems of ACE development are noted: (1) the desire for too much versatility for the ACE; (2) the effects of changes in prime equipment on ACE design; (3) the attempt to automate existing manual procedures.

Eight functions are performed by most ACE designs: programming, signal stimulation, comparison, conversion, evaluation, readout, memory, and switching. "It's hard to believe that, even with much more sophisticated equipment, man will ever be completely removed from checkout." Among the functions left to man is his ability to "understand the peculiarities of the machine in a variety of situations and allow for them."

Can a universal test set be built? The answer depends on the meaning of universality, but systems such as the Nortronics Datico and the RCA Dee can test a great majority of the functions of present missiles and electronics systems.

Since ACE itself is not completely reliable, the question of "who checks the checker" is often raised. This question does not necessarily lead to an infinite regress of equipment proliferation, and there is already evidence that proper design (e.g., the Army's Falt System) can "check the checker" in an efficient way.

A trend is foreseen away from the present serially-programmed equipment, to parallel-programmed tests under central computer control. Among the advantages claimed for parallel diagnostic tests are faster checking, less severe test point constraints, easier marginal detection in complex networks, and the fact that refinements, such as life prediction and

parts ordering, can be built in. Arguments against the parallel concept are the complex computer program required and generally high costs. For the short-term future, "incremental" gains in ACE engineering are anticipated: higher speed, greater accuracy, more test points, and more test storage.

16. Imus, H. O., "Tomorrow's Quality Demands," IRE Trans. Reliability and Quality Control, PGRQC-13, July, 1958.

The author identifies some general factory automation trends and their consequences on personnel, complexity, standardization, precision, and speed. He identifies and discusses specific consequences of automation on quality control, personnel, precision, and production cycle time.

Quality Control. "Test and inspection equipment will be mechanized and mechanically integrated into the production system. This is part of the ultimate overall automation philosophy as discussed previously. The test and inspection equipment of today is almost completely manual or only partially mechanized, comparatively far behind production equipment. There is, however, equipment either on the drawing board or in the market that is fully mechanized.

"Statistical analysis will be built into...automated inspection equipment. Information obtained by the inspection equipment will be fed back into the machine computer. The computer controls the position of the tool, compensating for tool wear and machine drift.

"Post-production inspection is common today. Automation will emphasize in-production and pre-production inspection. In-production inspection will provide quality information while the part is actually being produced.

"One hundred per cent inspection will become more widespread. In many cases automated equipment to inspect output 100 per cent will cost only a little more than equipment to inspect 10 per cent.

"The most critical quality control activity will take place prior to actual production. Decisions will be made at that time to fix the level of quality. New design control will be a must in the automated factory as automatic equipment tends not to be flexible."

Personnel. "In the automated production line the human factor is minimized, and also the importance of quality-mindedness. Therefore, quality-mindedness must be emphasized with engineering and planning personnel. The personnel dealing with automation will of necessity have higher qualifications than today's hand-assembly factory laborer ....Inspectors, as such, just won't exist and in their place will be highly skilled inspection-test equipment setup and maintenance personnel. Test and inspection planning will be more elaborate."

Precision. "With the advent of products demanding and machines capable of producing parts to tolerances in the tens of thousandths and micro-inches,* the quality control function must make adequate provision to match these tolerances."

Production Cycle Time. "Customers are...demanding that we substantially reduce the production cycle time. With the time squeeze on all functions, it is well that all quality control objectives, methods, and responsibilities be recognized and integrated well into the pattern of a fast operation."

17. Latta, W. B., "The Army Outlook on Maintainability," in F. L. Ankenbrandt (ed.), Electronic Maintainability, Vol. 3, Reinhold, New York, 1960.

Maintainability is a "two-edged sword of management." One edge relates to the reduction of logistics requirements; the other treats maintainability as an aid to "decisions concerning our equipment inventory as it rapidly obsolesces."

The Army's Review Point Program directs attention to maintainability throughout the procurement cycle. A continuing problem is adequate definition: "From where I sit in the Pentagon, it may take ten years or even a second ten years to arrive at our goal of measurable contractual language to define ease of maintenance in Army equipment. There are a number of equally fundamental answers we must obtain in order to measure maintainability." Objective functions are desirable, but have not yet been derived, for the various costs involved in keeping a repair part in the system, for repair costs by the technician, and for the throw-away module policy.

A brief history of contract effort on the AN/GRC-66 Radio Relay is given as an example of a maintenance-oriented contract. On the basis of field experience with an earlier model (AN/TRC-29), the number of circuits was reduced; the failures to be expected in the new system are largely limited to modules that can be stocked in forward echelons.

Many variables affect equipment obsolescence; e.g., class of equipment, elapsed time since the item was developed, rate of technological advance, budgetary and production resources, and operational criteria. Obsolescence curves are related to calendar time, maintenance-required-to-restore, and reliability. An "index of competitiveness" is proposed to measure the worth of retaining equipment items in the system. The index is now being applied to four types of electronics equipment.

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*"The Inchworm Motor, manufactured by the Airborne Instruments Laboratory, Mineola, Long Island, New York, controls certain metalworking machines to hold dimensions to plus or minus five micro-inches."

18. Lewis, J. L., "Integration of Maintainability Requirements into the Research and Development Phase of Weapon Systems," in F. L. Ankenbrandt (ed.), Electronic Maintainability, Vol. 3, Reinhold, New York, 1960.

Because of budgetary limits, increasing complexity, and short military reaction times, "it is unlikely that we will ever again have more men or material than we need to do a job."

"In summary, what is needed from the Air Force point of view is an adequate and integrated program to implement the requirement that weapon system components be serviceable and repairable. This effort must begin at the time equipment design begins.... The philosophy of the maintenance concept that is to be used in a specific system must be developed in its generic entirety, as far down in specific detail as can reasonably be described, in the planning phase."

19. Manley, R. W., "Management Techniques for Achieving Maintainability," in F. L. Ankenbrandt (ed.), Electronic Maintainability, Vol. 3, Reinhold, New York, 1960.

A discussion is presented of "roadblocks to maintainability" that must be overcome "by any organization which is to be successful in designing, developing, and manufacturing maintainable electronic hardware." These factors include disinterest of designers, unsuitable organizational structure, lack of design review system, and mishandling of field information.

The techniques adopted for assuring combat readiness (and, therefore, maintainability) of the Falcon missiles are described. One of these techniques is to set aside one test model for maintainability study; this missile is completely tested, disassembled, and reassembled with field maintenance tools. Careful records are kept of tests, repair parts, and other facts of maintainability significance.

20. Miller, R. B., Anticipating Tomorrow's Maintenance Job, USAF Air Training Command, Research Review 53-1, March, 1953, 21 pp.

An "equipment-demands" analysis conducted on a prototype equipment can be used to predict requirements for the production equipment. A sample application of the method to the Q-24 radar showed a remarkable correspondence between the prototype and production models. Some practical implications are that (1) mechanics can be trained before equipment is obtained, (2) basic or "core" courses can be set up for related but different jobs via common job-derived activities, (3) technical manuals can be written in behavioral language, and (4) job design can proceed simultaneously with the early stages of equipment design.

21. Ozkaptan, Halim, "Maintenance Problems of Space Flight, " in F. L. Ankenbrandt (ed.), Electronic Maintainability, Vol. 3, Reinhold, New York, 1960.

The unique features of maintenance in space are pointed out: logistics, "fallback" resources, special planning, and psychological problems such as weightlessness, confinement, and time criticality. Troubleshooting, the major factor in repair time, is postulated as the area in which the greatest returns relative to support effort can be achieved.

Past efforts to aid the troubleshooter have usually taken the form of special manuals, equipment layout, and test point selection. "However, these have only served as aids to the technicians' capability without substantially increasing it. A more significant point is that they also require decision and application in themselves. Voluminous manuals present a task in their application which is almost as formidable as the troubleshooting problem. Similarly, training in basic electronics does not transfer directly to the troubleshooting process. For space and other remote complex systems, a direct amplification of troubleshooting capacity is required to keep pace with increasingly complex systems and decreasing repair time available. In other words, since the scope of equipment is surpassing man's ability to diagnose it, equipment must be used to amplify this capacity rather than supplement it."

How is this amplification to be achieved? "In the past we have amplified human performance in our advanced systems through such means as servomechanisms and special displays. For troubleshooting, a similar approach can be employed relative to an optimum continuation of human and equipment abilities. Computers which have greater rote memory and speed of association than humans can be used effectively in combination with man's greater power of sensory discrimination and flexibility. The components of a system and their relationships can be programmed into a ground-based computer. Depending on the amount of failure information or symptoms which can be determined and remotely fed by the astronaut to the computer, it can run trial solutions and either idenfity the failed component, give decreasing probabilities for the failed component, or indicate additional information needed. This would represent computer amplification of the troubleshooting process itself, supplementary to the capability of the maintenance technician."

A central computer installation could be set up to service a large area and many different systems. Data-link interrogation of the central computer would permit distant but rapid troubleshooting, since the remote technician could send in masses of test indications and the computer could send back preliminary interpretations and guides to further checking.

For such an arrangement to work, the optimum configuration of man and computer must be set up. The computer might be programmed to store all imaginable faults, with each related to a pattern of symptoms. A more sophisticated approach would involve a dynamic model of the internal characteristics of the system, along with "simulation runs" that depend on logical relationships to indicate probable failed units. This second method is the most appealing, but would require much development effort.

Some problems in man-computer communication and in the implementation of the maintenance center are briefly examined. Potential advantages

of the center include preventive maintenance programming, inventory and logistics tabulations, and the collection of reliability statistics. If the concept is successful, the training and skill levels of technicians might be materially reduced; at the same time, troubleshooting aids and manuals could be simplified.

22. Steele, G., and P. Kircher, The Crisis We Face, McGraw-Hill, New York, 1960, 220 pp.

This book identifies the management and design problems that accompany the use of automatic data processing systems. Some "horrible examples" are described in which missile programs have been victims of an unbalanced and unrealistic attitude toward automatic testing. However, the authors foresee a tremendous advance provided management realizes that technological changes are occurring. Many suggestions are given for professional management training; one of these proposes a seven-year college course emphasizing the engineering and data processing sciences.

23. Still, W. L., "A Rebuttal by the Military," Control Engineering, Vol. 7, No. 12, December, 1960, pp. 77-83.

This article is a vigorous refutation of Steele and Kircher's The Crisis We Face (see Item 22). It is contended that the authors' extrapolation from Atlas to Minuteman is faulty, and that the Minuteman actually represents a considerable simplification in equipment and procedure. For example, "Command and control of the (Minuteman) missile originates in the Launch Control Center, the manned post from which two men govern all missile functions. The message structure to control the automatic force consists of a total of six commands transmitted from the Launch Control Centers." As for the data fed back from the launch site, "less than a dozen discrete status signals are returned from the missile." The targeting procedure hypothesized by the authors for the Minuteman is also criticized.

Steele and Kircher's analyses of Minuteman component parts and reliabilities are questioned on both numerical and logical grounds. A new Minuteman approach to treatment of failure data is described in which each failed component is sent to a "Physics of Failure Laboratory." It is maintained that "by taking all possible known preventive steps from initial component manufacture, and operating on the premise that there is no such thing as a random failure, we can gradually improve manufacturing, engineering, handling, and operating procedures to approach our reliability goals."

24. Swain, A. D., and J. G. Wohl, Factors Affecting Degree of Automaticity in Test and Checkout Equipment, Dunlap and Associates, Inc., Stamford, Conn., TR 60-36F, March, 1961.

A survey of problems in the design and use of automatic checkout equipment was directed at specifying both formal and informal factors that affect (1) the degree of automaticity designed into test and checkout operations, and (2) the field acceptability of ACE. Interviews were conducted with design and research personnel in the areas of prime equipment and test equipment design, maintenance training, and human factors. Interviews and observations were conducted at a number of operating military sites. A literature search was made of reports on design and experience in the areas of maintenance testing.

On the basis of the survey, the report describes current allocation of test and checkout operations between man and machine, and shows the implications for the effectiveness or ineffectiveness of field operations where test and checkout equipment is used. Overriding (or "super") factors and compromises affecting ACE implementation are emphasized.

Recommendations are made for a systematic allocation procedure, and some allocation guidelines are presented. These guidelines vary from discussions of specific weapon systems and specific criteria to a more general treatment of those tasks that man or machine does best, and the various conditions under which the superiority of each is reduced or reversed. Finally, suggestions are made for design features that can improve the compatibility of ACE with its operating environment, and for a more efficient role of man in the maintenance process.

25. Toffler, J. E., "Some Typical Problems in the Design of Automatic Test Equipment," Electronic Industries, Vol. 20, No. 1, January, 1961, pp. 76-80.

Problems in designing a high-speed, automatic system to be used for missile checkout by unskilled personnel are discussed. The only decisions required of the operator are minor adjustments, test initiation, and the like. The checkout is controlled by a master tape, so that tests can be changed by merely changing the program tape. About five tests per second are to be accomplished.

One kind of problem was that in which the engineering solution was reasonably straightforward, but the implementation would add enormously to over-all system complexity. An illustration is given for the case where seven bits of information are sensed to energize 2^7 or 128 relays. A large number of gates and flip-flops may be necessary to ensure this (logically) simple capability.

A second problem area was that of "non-off-the-shelf" items. If one needs a counter which is to be controlled by binary code, it may be necessary to modify extensively a conventional counter. Or the designer may have to design his own special meters to meet peculiar measurement needs.

Sometimes the physical realities are in direct conflict. For example, it may be desirable to obtain a filtered voltage reading within a very

short time interval. But adequate filtering takes time, and something must be compromised.

Despite such problems, ACE capabilities are improving rapidly. The author predicts a further trend toward high-speed, automatic digital test devices; he states that the most important step in a practical ACE program is the detailed statement of test requirements. These should be instrumented first, before luxury features are added.

26. Willow Run Laboratories, Proceedings of the Symposium on Digital Simulated Techniques for Predicting Performance of Large Scale Systems, Report No. 2354-33-x, May 23-25, 1960.

A collection of about twenty papers pertaining to the digital simulation of large systems. Generally, these systems are military defense or detection systems, not computers. The digital techniques discussed are specialized and do not involve the use of a general-purpose computer. Maintenance and checkout are not considered in detail.

III. MAINTAINABILITY DIRECTIVES AND GUIDES

27. Air Force Ballistic Missile Division, Design for Maintainability Program for Weapon and Space Systems, AFBM Exhibit 59-32, June 16, 1960.

"The overall objective of this program is to obtain optimum ease and economy in all maintenance required in support of a weapon and/or space system. To achieve this objective, it is a fundamental requirement that maintainability must be considered in the initial stages of design and engineering. Maintenance tasks which are required must be identified, and provision made for these actions. Maintainability must be engineered, designed, and built into the operational hardware, support and ancillary equipment, and check-out and maintenance components of the weapon or space system."

To accomplish the above, the contractor is required to prepare an explicit maintainability program for his weapon system, identify the organization to implement this program, have this organization provide design engineering with maintainability guidelines, include pertinent maintainability criteria in each equipment design specification, and provide for functional and environmental testing of the design to demonstrate that maintainability requirements have been met.

28. Department of the Air Force, Maintainability Requirements for Weapon, Support, and Command and Control Systems, and Equipment, MIL-M-26512A, December 5, 1960.

This specification "establishes the maintainability design, analysis, and data requirements for weapon systems, support systems, and command and control systems, and Air Force equipment and provides policy and general procedures for a maintainability program by the contractor."

From the initial design stages, the contractor is required to include maintainability as a specific area of effort, identify it as a part of the over-all system analysis, and predict maintainability characteristics. This program shall be carried forward by a "single organization or group. The contractor shall identify this single organization or group, and shall define clearly its responsibilities. The contractor shall also stipulate the authority delegated to this organization to enforce its policies and to ensure necessary action toward maintainability."

"Proposals for new systems shall include quantitative maintainability objectives" and if "maintainability parameters are not known,...(the contractor) shall estimate the maximum permissible values of the maintainability parameters." Care must be taken that "criteria, pertinent to the design for maintainability of the manufactured product, are provided for the use of each design engineer, and the data provided ...shall be updated on a continuing basis."

General maintainability principles are listed and some design trade-offs involved in operational effectiveness or logistics mentioned.

Three definitions of maintainability are presented:

"a. Maintainability (Organizational). - The capability of an equipment to be returned to an operational status in a specified period of time.

b. Maintainability (Field). - The capability of an equipment to be returned to a serviceable status with specified test and repair equipment within a specified period of time.

c. Maintainability (Depot). - The capability of an equipment to be overhauled and returned to a serviceable condition at a specified per cent of unit cost.

"Availability is the ratio between the time the article is available for use and the total time (time available for use plus time not available because of maintenance being done or repairs being made)."

29. Dunlap and Associates, Inc., Human Factors Design Standards for the Fleet Ballistic Missile Weapon System, Vol. 1, Bureau of Naval Weapons, OD 18413, June, 1960, Chap. 7.

A method for scoring the maintainability of an equipment is presented. A large number of guidelines are listed, and each has been pre-rated according to four factors:

1. Importance, i.e., the extent to which down time is reduced
2. Effect on available equipment volume
3. Effect on equipment cost
4. Effect on equipment reliability

Ratings are based on whether the guideline is believed to have a large, medium, small, or no effect on each of the four factors. For example, one guideline might state that a power on-off light should be provided. In a given application, this might be judged quite important (high score on Factor 1) and yet have no significant influence on gear volume, cost, and reliability (low score on Factors 2, 3, and 4). The design implication is clear: put in the indicator. For other situations, the design implication is more complex because high- and low-factor components must be traded off.

30. Fitzpatrick, Robert, et al., The Design of Test Devices for Preventive Maintenance of Ground Electronic Equipment, RADC Technical Report 58-172, September, 1958, 77 pp.

The objective of this study was to develop test measurement techniques (from the human engineering point of view) for the preventive maintenance of ground electronics equipment by relatively inexperienced GS 3- and 5-level maintenance men in the Airways and Air Communications Service.

An initial survey indicated that test measurement requirements in five years are likely to differ little from those of today. Hence, test measurement requirements were abstracted from AACS Preventive Maintenance Instructions for a representative group of prime equipments. Various tables were drawn up to show the ranges of electrical properties required.

On the basis of the test measurement requirements and a series of ten design criteria, displays and controls for thirteen proposed devices were designed. Drawings and descriptions of these devices were prepared.

The study indicated that the proposed devices would be adequate, and that the methods developed in the study could be used to develop an integrated group of test devices that would be widely applicable in the Air Force.

31. Folley, J. D., Jr., and J. W. Altman, Guide to Design of Electronic Equipment for Maintainability, WADC Technical Report 56-218, April, 1958, 174 pp.

"This guide was written to provide principles to be applied during electronic equipment development for 'building in' provisions for more effective maintenance." It includes recommendations for designing maintainability into equipment and into the primary maintenance supports--maintenance procedures and job instructions--and describes a schedule for incorporating maintainability into the operating situation. The guide is written for "designers," including those who prepare the military specifications and later more detailed specifications, equipment and maintenance support developers, monitors, and those who evaluate the operational suitability of systems.

Maintainability is defined as the rapidity and ease of performing preventive and corrective maintenance operations. Reliability is defined as the probability that a product will perform suitably over a given period of time, assuming the product is used for its intended purpose. Thus, poor maintainability can reduce reliability.

The need for systematic consideration of maintainability supports (test equipment, logistics, personnel, tools, procedures, etc., as well as the prime equipment itself) is stressed. The importance of coordinating maintainability features by conferences, periodic reports, and face-to-face meetings of all designers is also emphasized.

Recommended characteristics for maintainable equipment are presented in 90 pages of detailed written and graphic items for equipment units. The coverage includes racks and cases, interconnecting wires and cables, accesses, test points, controls and displays, control-display relationships, installation of prime equipment, test equipment, bench mock-ups, and tools. The treatment of test equipment is relatively brief, as reference is made to the Spector, Swain, and Meister report (see Item 74). It is noted that the main advantage of automatic test equipment is that it can make a rapid sequence of checks with negligible variability or

without omitting any steps. ACE has several disadvantages: high cost, size, weight, and maintenance requirements; low versatility; need for self-checking features which add to cost and to problems of maintenance of test equipment; and the greater likelihood of requiring modification.

Twenty-six pages are devoted to "considerations in preparing procedures." "Poorly designed procedures can offset the benefits of otherwise good design for maintainability," and "delaying preparation of procedures until after the equipment is designed is likely to yield poor maintainability." The importance of maintenance procedures for the user rather than for the design engineer is stressed.

The use of special maintenance diagrams for analysis of symptom patterns is urged. Since the number of possible patterns is very large, a "pattern-group" method is suggested. Samples of maintenance procedures for routine checks and troubleshooting are presented with emphasis on flow diagrams which relate signal information to detailed step-by-step instructions. The intent is to reduce the amount of general electronics information the maintenance technician must have by providing job aids that reduce the number and complexity of decisions required.

32. Hall, N. B., C. E. Van Albert, and J. H. Ely, Recommended Equipment Coding to Facilitate Maintenance, RADC Technical Report 59-159, September, 1959, 23 pp.

A number of AFSC GS 3- and 5-level maintenance personnel at five sites of the Airways and Air Communication Service were observed and interviewed at preventive maintenance checks and troubleshooting on radar and electronic communication equipment. It was recommended that the following additional types of information be coded on prime ground electronic equipment:

"1. Designation of functional groups: Such a designation assists the technician in thinking of functional groupings and in isolating malfunctions to such groups. The construction of much equipment is such that to a large extent components within the same functional group are placed together; however, no indication is made on the equipment of this grouping. Schematics often have functional groups outlined, which necessitates continual cross-reference between the schematic and the equipment proper. This procedure is time-consuming and, in some cases, inconvenient when the technician must handle manuals within a confined space.

2. Indication of signal path: To some extent signal paths are indicated on schematics and on equipment, but in the latter situation, they are usually difficult to follow. An indication of signal path shows the technician which functional groups interact as well as the normal flow of signals through the system.

3. Identification of test points: Although test points are usually easy to locate, their importance or the sequence in which they should be used is seldom indicated on the equipment. Proper coding of these points provides a suggested test procedure which may be followed by the technician at his option. It aids in bridging the gap between the clean, orderly circuit diagram and the less than orderly equipment.

4. Presentation of historical data showing obtained values at particular test points: The field observations and questionnaire results indicate that the divergence of measured values at test points from those recommended in Technical Orders and Preventive Maintenance Instructions confuses technicians and makes troubleshooting more difficult. It does not appear feasible to change the values in the manuals because the proper values appear to vary from equipment to equipment and within the same piece of equipment from time to time. However, the past history of readings at test points taken when the equipment was operating satisfactorily can provide the technician with a dynamic standard for comparison with any readings he obtains while troubleshooting the same piece of equipment.

These recommendations were tested by selecting two identical DuMont oscilloscopes, Type 274A, and providing one with the coded information in the form of colored areas and components, special patterns, arrows and other lines of various sizes and forms, special symbols, and arabic numerals. Eighteen technicians were used as subjects, eight for the coded and 10 for the uncoded. Average experience for the coded group was 1.9 years and for the uncoded group 3.3 years. Twelve malfunctions ranging from easy to difficult were introduced and the times required to locate each were obtained. The mean (arithmetic) time to find a malfunction on the coded scope was 23 minutes (with a range from 5 to 68 minutes), whereas the mean time for the uncoded scope was 42 minutes (with a range from 3 to 168 minutes). The differences were statistically significant beyond the 1 per cent level. The results also showed that coding the equipment did not help experienced technicians or the identification of easy malfunctions, but it considerably helped the inexperienced technicians, particularly in their locating and identifying difficult malfunctions.

The findings and recommendations of this study (including examples of the coding recommendations) were presented to ten RADC engineers. The first three recommendations were accepted by the engineers with little or no reservations, and the last with some reservations.

33. McKendry, J. M., et al., Maintainability Handbook for Electronic Equipment Design, Naval Training Device Center, Technical Report 330-1-4, April, 1960, 387 pp.

Eleven chapters are devoted to topics such as the working environment, test equipment, circuit specifications, components, connections and housing, function controls, and labeling.

34. Miller, R. B., and J. D. Folley, Recommendations on Designing Electronics Equipment for the Job of Maintenance, Air Training Command, HRRC Research Bulletin 51-33, December, 1951, 18 pp.

"It is important to know the maintenance job requirements in advance of production models of newly designed equipment in order that suitably trained mechanics will be available when the equipment first gets into the field....Maintenance job requirements can be anticipated in three ways....First, maintenance tasks should be simplified by the way the equipment is designed....A second approach...involves compiling, under the categories of checking, adjusting, troubleshooting, replacing, and repairing, those discriminations, decisions, and actions as are indicated by the design of the production model itself....A third approach consists of keeping appropriate records of maintenance operations which are performed during prototype testing of newly designed equipment.... Standard Maintenance Form data should be used to supplement and weight the job behaviors obtained by the second approach.

"It can be expected that the systematic integration of equipment design, maintenance training, and maintenance operations will lead to a higher degree of reliability and efficiency in the use of the equipment and a reduction of personnel requirements necessary for achieving satisfactory maintenance of equipment."

35. Van Albert, C. E., N. B. Hall, and J. H. Ely, Coding of Equipment for Ease of Maintenance, RADC Technical Report 59-160, October, 1959, 8 pp.

This report was prepared for design engineers and summarizes the recommendations resulting from a human factors study of maintenance. A description of the entire project may be found in RADC TR-59-159 (see Item 32).

ADDITIONAL REFERENCES

Wohl, J. G., "Dependability of Military Equipment: A Systems Approach," Electrical Manufacturing, Vol. 3, No. 3, March, 1959, pp. 96-100.

Wohl, J. G., "Why Design for Maintainability," IRE Convention Record, March, 1961.

IV. MODELS OF THE MAINTENANCE PROCESS

36. Ashar, D. G., Probabilistic Model of System Operation With a Varying Degree of Spares and Service Facilities, IBM Data Systems Division (n.d.).

"The techniques for evaluating the probabilistic properties of systems having identical operational and spare units with different facilities for repairs are discussed in this paper. The important properties studied are:

(a) Reliability and transient behavior of systems.

(b) The expected values of times to failures and the measure of variations from the distributions of system failures.

(c) Asymptotic or steady state probability of such a system being in unavailable state.

"The general expressions are obtained for many cases, while the methods are illustrated by a simple practical example."

37. Bovaird, R. L., and H. W. Karr, Applicability of Quantitative Analysis to Problems in Maintenance Management, General Electric Co., R 58TMP-18, June, 1958, 34 pp.

"This is a report on a brief study to determine the possibility of applying mathematics and economic theory to maintenance management problems. In Section I routine operating decisions are described and analyzed with the aim of discovering where quantitative methods of analysis appear applicable. Long run decisions are also considered with the same aim.

"In Section II a cost minimizing maintenance model is described which takes account of such factors as deterioration and failure probabilities, man-hours for preventive inspection and preventive repair, elapsed time for emergency diagnosis and repair, cost of setting up for periodic maintenance, cost of maintenance men, and cost of system downtime. This model is demonstrated with a numerical example illustrating how it can be used to determine the optimum time between periodic maintenance, the optimum number of maintenance men, and at which periodic to inspect each item."

38. Boviard, R. L., and H. I. Zagor, "Deriving Operational Availability from Sub-System Maintainability and Reliability," in F. L. Ankenbrandt (ed.), Electronic Maintainability, Vol. 3, Reinhold, New York, 1960.

A method for estimating availability in terms of operational modes and equipment groups is presented. Each group has associated with it certain reliability (mean down time per failure) data. Equipment survival likelihoods can then be obtained by simple combinatorial methods, and can be specified as part of a procurement contract.

Often some operational capability exists even if one of the major equipment groups fails; if enough of the subsystems fail, however, the system is totally ineffective. By setting up a table of the effectiveness under the failure of different equipment groups, a "marginal effectiveness" measure can be derived for each group. This measure can be used to suggest maintenance strategy. For instance, if restoration of equipment group A would raise over-all effectiveness from .18 to .37, allocation of principal maintenance effort to group A should be more efficient.

It is suggested that a tactical worth parameter (product of effectiveness and reliability) be investigated as an aid to tactical decision making.

39. Brunner, L. K., L. J. Clevenger, and G. W. Dodson, A Method of Identifying, Quantifying, and Specifying the Objective Predictors of Maintainability, Air University School of Logistics, Wright-Patterson AFB, June, 1960, 68 pp. and three appendixes.

The discussion begins with a critical review of six official Air Force maintainability directives (DOD 3232.1, AF Regulation 66-29, Mil-M-26512, AMC Manual 66-2, AMC Manual 66-5, and Proposed AFBM Exhibit 59-32). Four deficiencies are common to all: (1) evaluations are conducted too late in the development cycle; (2) evaluation criteria are too general and too judgmental; (3) reliability and maintainability are evaluated separately rather than jointly; (4) though responsibility for maintainability is shared by AMC and ARDC, only ARDC has authority.

Nine different phases in the development and production cycle are defined and the kinds of tests and reviews in each phase are given. A definition of maintainability in terms of "mean time to repair" is given; this measure is coordinated with the "mean time to failure" conception of reliability. "Availability" is the ratio of reliability to reliability-plus-maintainability. Besides this algebraic tie between the two concepts, the point is made that "reliability... can be designed into a system and exist in a pure state independently of maintainability considerations,... but maintainability features cannot be applied to a design in an intelligent manner without prior consideration of component reliability."

A chapter on reliability statistics and failure curves summarizes many analytic techniques. As yet there is no agreement on the meaning and combination of basic maintenance terms; many approaches to and definitions of maintainability are quoted to illustrate the diversity of opinion.

In computing a maintainability index for competing systems, "delete from consideration those factors that are specified in the contract and are constants in comparative analysis between systems during source selection. Since they are beyond the control of the contractor, he should not be given credit or penalized for their effect on the overall maintainability index."

Maintenance task time and frequency are estimated for each sub-assembly. Formulas for computing different kinds of down time are given. An availability parameter is suggested as the best mix of reliability and maintainability:

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR} + \dfrac{\text{MTBF}}{\text{MTBIS}}(\text{MTTIS})}$$

where MTBF = mean time between failures
MTTR = mean time to repair failures
MTBIS = mean time between inspection and service
MTTIS = mean time to inspect and service.

40. Cooper, Joel, "An Integrated Approach to System Maintainability," in F. L. Ankenbrandt (ed.), Electronic Maintainability, Vol. 3, Reinhold, New York, 1960.

Since a high percentage of malfunctions are initiated by humans, a method for estimating the "human reliability" of a system would be useful during the planning and development sequence. It is proposed that classifying maintenance operations and collecting data on time, accuracy, and variability in performing them would be useful. Such data could be applied, for example, to the man-machine allocation problem: If human response variability for a set of operations is too great, then that group of tasks becomes a good candidate for mechanization or procedural revision.

Equipment attributes, maintenance actions, and maintenance level are determining features in system design; in order to investigate the relations among elements of these three "primaries," a three-dimensional matrix is suggested. For a particular maintenance level (e.g., depot) there would be a separate two-dimensional matrix of equipment attributes-by-actions.

Regarding the relationship between this method and the SAIM matrix (see Item 51), the author suggests that "it would be possible to consider the system at a general level under the SAIM method and translate to the maintainability matrix as proposed here with no problems in transition."

41. Davis, R. G., Preference Structures and the Measurement of Military Worth, Princeton University, Econometric Research Program Memorandum No. 17, September, 1960, 124 pp.

This monograph deals with the determination of "military worth functions." Typically the analyst begins with some preference judgments expressed by competent military authority; the judgments may be rankings or ratings. By making assumptions about "rationality," axiom structures can be set up to analyze such data. Several axiom systems are examined, with particular attention given to the Aumann-Kruskal method of computing numerical utility functions.

42. Depian, Louis, Reliability Using Redundancy Concepts, George Washington University, February 1, 1959, 18 pp.

The question of how imperfect circuits may be combined to achieve improved reliability is discussed. Two methods are described: (1) multiple circuits, a majority of which is required to provide an output; (2) multiple circuits whose output is averaged. A mathematical treatment shows the averaging technique to be more advantageous.

43. Grodsky, M. A., G. W. Levy, and R. D. Sorkin, A Model of Human Maintenance Behavior - I: Development of the Problem and Evidence for a Model, The Martin Company, Engineering Report 11133, 1960.

Four criteria are suggested for studying the advantages of automatic or manned modes for space flight: payload weight, economy (over-all operational costs), utility of man, and mission effectiveness.

Previous studies indicated that application of these criteria justified a manned vehicle. "It is apparent that there is a definite per cent weight advantage in using a manned mode of maintenance as opposed to an automatic mode of maintenance. It should be noted that the increased weight in the manned mode of maintenance also includes the weight required to support men within the system." These savings may be attenuated in the actual case because equivalent or greater cost expenditures would be necessitated by the selection and training of personnel to perform maintenance.

An idealized graph shows relationships between cost and degree of automation. "There is a payoff point between these axes where the combination between manned and automatic systems gives an optimum low cost. This 'payoff' point is not yet known and we are paying a large penalty for this lack of knowledge....Our main justification for man within the system was that man would cost no more than an automatic system and we could use his other abilities which are more difficult to quantify, such as decision-making, to make the system more effective."

Initial steps toward the development of a theoretical model of human maintenance behavior are described; the principal concepts are taken from signal detection theory and game theory.

44. Lowder, R. G., Considerations in Prediction of Maintainability, WADC Technical Note 59-378, November, 1959, 7 pp.

Defining maintainability as the "capacity for being kept in a state of good working order," this report reviews the problem of predicting the maintainability of a system before the system goes into production. Several approaches to maintainability are listed:

1. BuShips Index: $1 - \dfrac{\text{total time out of operation for maintenance}}{\text{total time possible to operate}}$

2. U. S. Army Signal Corps Index: Summed scores on a "yes-no" type of maintainability checklist

3. General Electric Index: Mean failure rate for a given type of component
Number of components of a given type
Mean repair time for the given component

4. Republic Aviation: Summed mean-time-to-fix for the various maintenance tasks

Each of these four approaches is based on a sampling scheme. Thus the Signal Corps approach samples the human engineering aspects, the BuShips index samples over-all availability, and GE samples individual component failures. "In that sense, each has taken a sample, but a limited one consisting of one factor out of a population of factors. Presumably, it would be preferable to be more extensive in selection of factors affecting maintainability and less comprehensive in the treatment of each."

Twelve factors that may lead to a quantifiable index of maintainability are:

1. Expected life span of components
2. Frequency of recommended inspections
3. Number of access parts or openings
4. Skill level required of maintenance personnel
5. Number of adjustments recommended during periodic maintenance
6. Number of test points for use during inspections
7. Number of built-in test equipments
8. Number of places where "quick-disconnect" fasteners were not used when they could have been used
9. Number of work spaces that are too small according to recommended standards
10. Number of special tools required
11. Number of special test equipments needed
12. Number of components that cannot be reached for inspection and repair without first removing another component

45. Manly, Ron, Maintainability - Its Quantitative Specification and Testing, Thompson Ramo-Wooldridge, Inc., Report C23-8015 (n.d.), 28 pp.

Before he can decide upon a maintainability design, the planner has to have three kinds of information:

1. The general maintenance concept, what is done at each level, time allowable, etc.

2. Data on the relative importance of time, weight, size, cost, performance, etc.

3. A method for predicting the effect of a provision for maintainability on time or other system parameters.

A plan for obtaining adequate maintainability is detailed. Allowable maintainability times, maintenance environment, and broad concepts of work assignments at each echelon are determined by military authorities; the contractor has to formulate test equipment and procedures and show that these are adequate to handle a definite sample of failures.

The inclusion of a definite collection of failures as a part of the maintainability specification may have two advantages: (1) it forces the designer to work through in step-by-step fashion the equipment and procedure necessities for fault location and checkout; (2) a collection of ten or more troubles can provide a good estimate of actual maintainability times, even though no rigorous sampling scheme has been followed in establishing the collection. Of course the "specified" troubles will represent the actual maintainability times better if the failures selected are those apt to be "most frequent," and if failures from each of the system subunits are included.

An illustrative test procedure for a helicopter system is given. "Half-split" troubleshooting is used, so that each conclusive check should test about half as many subunits as the previous check.

46. McGrath, J. E., and P. G. Nordlie, "Theory of Allocation of Functions to Man and Machines," in Synthesis and Comparison of System Research Methods, Human Sciences Research, Inc., Report HSR-RR-60/1-SM, February, 1960.

Since machines are no longer mere extensions of human motor functions, the performance capabilities of man and machines are competitive for many tasks. Due to stringent performance requirements of time, accuracy, and reliability, the question of optimum allocation of system functions assumes great importance. Moreover, the limited supply and the cost of the high operator skills needed in complex systems have led to efforts to reduce these high skill requirements.

The basic problem in function allocation can be stated as follows:

"1. Should human operator(s) be included in the system?

2. Where, or in what functions, should man be used?

3. How can the system be designed to capitalize on special or unique capabilities of the human operator?

4. How can man best be utilized to maximize:

    a. system performance capabilities?
    b. system reliability?
    c. system versatility?

5. How can man best be utilized to minimize:

    a. system cost (original and operating)?
    b. system complexity?
    c. development time?

"To treat man as a component of a system, we must be able to describe his properties and characteristics as a human operator in terms comparable to those by which we describe hardware components. This set of terms must be quantitative, so that direct comparisons between particular machine and human capabilities can be made. We are not yet capable of doing this except, perhaps, for a small range of human capabilities. Until such comparisens can be made, the problem must continue to be resolved on grounds less than systematic and objective.

"In addition, a logic of allocation decisions must be devised which will balance performance and cost factors such that an optimum solution results from its application. Such a logic must provide a means for specifying and measuring pertinent factors, and for combining factors to provide a unitary criterion for decision.

"Thus, a two-part approach is seen as being required for a solution to the allocation problem. First, a common, descriptive, quantitative language must be developed which can be applied to man and machine capabilities. Second, a logic of allocation decisions must be formulated. The two are clearly interdependent. The problem will receive major emphasis in Phase III of this research program."

47. Munger, M. R., and M. P. Willis, Development of an Index of Electronic Maintainability, American Institute for Research, Report AIR-275-59-FR-207, 1959. (Also, Instruction Manual and Evaluation Booklet to accompany the report.)

The Maintainability Index stems from a collection of 241 features designed to increase maintainability. These features are arranged under nine headings:

1. Displays and controls
2. External accessibility
3. Test points
4. Cables and connectors
5. Internal accessibility

6. Cases
7. Lubricants and tools
8. Manuals
9. Test equipment

Each design feature is scored according to its "consequences": maintenance time, logistics, equipment damage, and personnel injury. Summed scores can be compared against a pre-ordained maintainability standard.

48. Noriega, V., F. J. Jowdy, and J. M. Palmer, A Methodology for Determining Optimum Manning for Base Level Aircraft Maintenance, Air University School of Logistics, June, 1960, 66 pp.

How many and what kinds of men do you need to staff an aircraft maintenance base? The general answer is obvious: it depends on the number of major units, the complexity of equipment, the utilization of weapons, the proportion of time that ground and air alerts are required, etc. With so many variables, some kind of a systematic and self-correcting plan must be adopted for separating the significant factors from the less important ones and for producing definite manning tables from the operational demands.

A traditional method is to use "flying hours" as the basic indicator of manpower requirements. Air Force Manual 26-1 is a good illustration: starting from a flying-hour base, factor formulas yield organizational and field man-hour needs and manning levels. These levels are only starting points and are subject to local readjustment because of variation in mission, dispersal, facilities, etc. Thus, the optimum manning level remains a matter of individual judgment.

It is fundamentally wrong to assume that Aircraft X requires (say) 55.5 maintenance man-hours to produce an hour of flight, or that two flight hours will take 111.0 man-hours, or that reducing the flight time to zero results in a zero maintenance workload. The suggested analysis begins by separating the maintenance workload into constant and variable portions. The constant workload is incurred simply with possession of the aircraft; the variable load is tied to the amount of flight activity and may be divided into straight line (inspections, changes, etc.) and random (malfunctions, etc.). As implied by the name, straight line factors are reasonably linear with the number of sorties or flight hours. Random ground and air malfunctions, however, probably bear non-linear relationships to the operating schedule; e.g., it can be hypothesized that man-hour maintenance for air malfunctions is a negatively accelerated function of flight hours.

Starting from this broad breakdown of maintenance tasks, a procedure is described for estimating manpower requirements. The type, model, and number of aircraft to be serviced, and periodic inspection requirements furnish data for estimating constant workload. If available, historical data on time change requirements can be included.

Variable factors are harder to estimate but the Maintenance Data Collection System (described in Air Force Manual 66-1) should provide data that can be correlated against sortie and flight-hour figures. The authors anticipate high initial differences among units for the variable manning requirements; after sufficient data have been obtained, the average manpower spent on variable workload can become a quality control baseline.

After one goes through the procedure and has adequate estimates of average manpower requirements, "augmentation" or safety factors must be added to the manning levels. This is due to the random characteristic of failures: an average workload of five units will occasionally rise to ten units, and if provision has been made to cover only the five, a backlog will rapidly pile up. The authors propose the classification of weapon system capability into vital, essential, and required; this classification would be made at the highest command levels. The vital manpower levels are augmented by a certain safety-factor fraction; lower fractions are employed for essential and required systems.

49. Rome Air Development Center, Maintainability Measurement and Prediction Methods for Air Force Ground Electronic Equipment, RADC TN60-221, September, 1960, 281 pp.

This is the Phase II Progress Report of the RCA Maintainability Study described in Item 50. The basic correlation model is extended into a field phase, with maintenance time the principal criterion. Design parameters and personnel factors are clearly related to the time criterion and are moderately independent of each other. Design factors get the highest weight in the repression equation. Simulation and field maintenance aspects appear to be similar enough to permit extrapolation from one situation to the other. Part type, circuitry class, type of modules used, and technician experience are all related to maintenance time. The field support environment produces severe degradation with a ratio of about 3 to 1 between average field and laboratory times.

Plans and expected results for the next phase are projected. A scheme for validating the technician proficiency test is given; it will study the relationship between test scores and job-sample troubleshooting times on selected FST-2 malfunctions.

50. Rome Air Development Center, A Research Plan for Developing Methods of Maintainability Measurement and Prediction, RADC-TN-60-5, January, 1960.

This is the Phase I report of a program of identification and quantitative treatment of the principal factors affecting the maintainability of Air Force ground electronic equipment. Two practical goals are established: (1) increase availability of ground electronics equipment, and (2) reduce operational support cost. These goals will be achieved only by "the treatment of maintainability factors as fundamental, measurable design criteria that can be specified and controlled from equipment design inception through intended service life."

For equipment that is required to be on-line continuously, availability is defined by the ratio:

$$\text{Operational availability} = \frac{\text{operate time}}{\text{operate time + down time}}$$

Though both reliability and maintainability will influence the availability ratio, a distinction is made between these two concepts. Availability "is not directly related to the occurrence of failure, it is directly related to the effects of failure. It is the goal of the maintainability effort to reduce the <u>effects</u> of failure." Maintainability goals should be stated principally in <u>calendar</u> time and not in total man-hour expenditure.

Seven factors that affect the degree of maintainability are:

1. Quality of design
2. Operational concept
3. Test equipment
4. Technical orders and instructions
5. Maintenance materiel
6. Personnel factors
7. Maintenance organization

Dangers of over-automating the test and checkout are recognized: "The degree of automaticity of performance monitoring, checkout, fault-location, marginal checking circuitry, etc., is almost unlimited; however, the resultant requirements for supporting circuitry can very quickly override the advantages obtained because of its own requirement for maintenance and checkout. Also, there must be a lower limit in the simplicity of required maintenance tasks which will result in a very low motivation of maintenance personnel as the maintenance task becomes a fully automatic routine. We need to guard against being chained by the magic of automation without recognizing the basic issues justifying it, namely, increased productivity, i.e., more work done by less men and materials."

Research of the correlation of maintenance task attributes with the time required to perform the task is proposed. Thus, separate scores can be recorded for access, packaging, test points, labeling, and fault indicator practices. Parameters such as training requirements, site factors, and maintenance instructions can be also systematically, if arbitrarily, scored. These scores can be considered to be "predictors" of the actual maintenance time required. The maintenance time information will be obtained from field and laboratory observation of trained technicians performing the work. It is expected that a multiple-correlation analysis will be carried out to derive empirical weights for the various predictors.

51. Shapero, Albert, and Charles Bates, Jr., <u>A Method for Performing Human Engineering Analysis of Weapon Systems</u>, WADC Technical Report 59-784, September, 1959.

The Systems Analysis and Integration Model (SAIM) attempts to indicate within a single framework the significant elements of a weapon system. A two-dimensional square matrix is used. Three main classes of elements are those that (1) determine the nature and form of the system, (2) constitute the parts of the system, and (3) integrate the parts of the system. Detailed breakdowns within these three classes are given; thus performance requirements are part of the system determinents, and can be categorized further into support performance requirements and operational performance requirements. Support could then be comprised of handling, storage, and so on. Subsystem matrices can be constructed and combined into a total system context.

The SAIM matrix can be used to record the interactions and influences among system elements. The insertion of interaction data is limited to "direct connections," one that does not go through a third system element. If a signal light goes on and a "hold" button is pushed, the signal light is not directly connected to the button because of the intervening human element (which is also listed on the matrix).

Second, third, and higher-order relationships can be shown on the matrix also, but "experience has shown that usually one or two re-entries are sufficient." As the design schedule proceeds, the relations become more explicit; "each interaction space in the matrix can be considered to be a file folder (or a reference to a file folder) within which is located the information pertaining to the direct relationship between two elements." Decreasing degrees of freedom will be observed as alternatives are eliminated and designs are firmed.

52. Terry, Herbert, "Game Theory in Product and Project Evaluation," paper read at Operations Research Society of America, New York, May, 1960.

The game theory viewpoint is applied to several problems in evaluation and marketing. For example, ratings of product goodness can be considered as "pay-offs," and item-criterion score matrices can be examined for "dominance" and the "value" of alternative strategies.

53. Thomas, R. E., et al., The Effect of Various Levels of Automation on Human Operator's Performance in Man-Machine Systems, Battelle Memorial Institute, June, 1960.

If a system is under-automated, the operators probably will be numerous, overloaded, and "connected" inefficiently. If a system is over-automated, the equipment will be complex and expensive and man will be relegated to a monitoring role. In either case, system performance will be degraded. Conceptually, at least, an optimum level of automation exists. The project described here attempts to develop an "automation model" for the function allocation problem.

As a start, three types of assessments are postulated: (1) recognize whether or not the system is within tolerance; (2) select corrective actions from a specified repertoire; (3) judge whether the corrective

action was effective in restoring system performance. These three kinds of assessments can be represented in an "automation cube;" the automation level of any system can be defined by the location of a point within the cube.

"The first year's efforts in this research program have produced several tangible results: (1) a qualitative model in which the automation problem is reduced to its essential features; (2) a quantitative model that includes two system parameters, a and b, and may be analyzed to determine the assessment cycle times, t_c, that will yield a desired probability of control, p_c, for given tolerance limits, ΔL, and specified magnitudes of the corrective actions; (3) an experimental apparatus that is capable of presenting to groups of subjects a wide variety of control problems characterized by the values of a, b, p_c, ΔL, and ci; and (4) the results of pilot experimental studies that suggest satisfactory agreement between the predicted and observed probabilities of control."

54. Wertheimer, F., and M. Morrison, "A Mathematical Model for Dealing With Critical Levels of Reliability Cost," paper read at Operations Research Society of America, Pasadena, California, November, 1959.

"An operations research study is presented which develops a method for dealing with the cost of reliability in system research and development. Although derived for a major weapon system, the model is applicable to other systems.

"A model is constructed which yields optimum system reliability as measured by total cost to achieve a stated mission. A relationship between levels of system reliability and cost to realize each level is assumed. In addition, the model accounts for a relationship which is postulated to exist between system accuracy and reliability. Specification of optimum system reliability on a cost basis therefore incorporates concomitant effects on accuracy."

55. Wrieden, E. G., "Design Considerations of Built-in Test Equipment," in F. L. Ankenbrandt (ed.), <u>Electronic Maintainability</u>, Vol. 3, Reinhold, New York, 1960.

Built-in Test Equipment (BITE) is usually expected to (1) assist during ground and in-flight maintenance and (2) confirm proper system condition during operational phases of the mission. It is desirable to estimate the effectiveness of a given BITE configuration, so that trade-offs can be accomplished against such parameters as weight and increased equipment complexity.

The evaluative parameter used here is "confidence level," which is "the probability that when a test is performed on a portion of a system and a go indication is obtained, that portion is operating within tolerance." Using experimental modifying terms to express reliability attributes of the system, confidence level formulas are derived for several different operating situations. It is possible to reverse the formulas and derive testing intervals from a confidence level which is stated in advance.

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V. HUMAN PERFORMANCE OF CHECKOUT AND FAULT-ISOLATION TASKS

56. Bond, N. A., Jr., "Maintaining Space Vehicles," paper presented at a meeting of the American Rocket Society, Los Angeles, May, 1960.

This paper discusses the behavior of trained personnel performing maintenance tasks for manned space flights. The principal recommendations are to (1) provide discreteness in the modularization of equipment so that the technician can troubleshoot as he does in a linear chain of elements; and (2) push failure prediction methods so that a large proportion of failures can be anticipated. The achievement of both these recommendations will probably involve major transformation of equipment parameters and packaging.

57. Bryan, G. L., and D. H. Schuster, An Experimental Comparison of Trouble Shooting Training Techniques, University of Southern California, Electronics Personnel Research Report No. 30, November, 1959.

On the hypothesis that furnishing specific guidance and explanations would provide superior training in troubleshooting, Navy electronic trainees were given three days of instruction and training using the DAS-3 Loran. Three levels of guidance (none, partial, and full) and two levels of explanation (none and verbal rationalizations of correct checks) were used. A standard criterion test in the pull-tab format showed that both guidance and explanation helped the student. A subsequent check showed that those who had received guidance training made higher troubleshooting scores on a live SPS-10 radar. The radar test was given by independent examiners four weeks after the experiment.

58. Bryan, G. L., et al., Electronics Trouble-Shooting: A Behavioral Analysis, University of Southern California, Electronics Personnel Research Report No. 13, March, 1956, 206 pp.

"Step-by-step protocols from four data sources are examined with the objective of developing a framework for behavioral analysis of trouble shooting. In an attempt to integrate various facets of such performances, qualitative segments are identified in each protocol, and reference is made to their frequency, position, consistency, and behavioral consequences. Separate treatment is given to special aspects such as redundancy, errors, time, and action rate. Throughout the report, attention is directed to generalizability of the results to different kinds of electronic equipment and to different test formats."

59. Bryan, G. L., et al., The Role of Humans in Complex Computer Systems: Maintenance, University of Southern California, Electronics Personnel Research Report No. 26, January, 1959.

"This investigation was designed (1) to observe and describe maintenance requirements and practices for digital computer systems now in use, (2) to examine the methods for screening, training, and evaluating computer technicians, and (3) to obtain up-to-date information on the organization and supervision of computer maintenance work. Visits were made to 50

representative computing centers in the United States; on-site information was collected by means of observation, questionnaires, and interviews.

"Three categories of maintenance activities are...checkout, scheduled maintenance, and troubleshooting.... Checkout includes all the procedures for testing the computer and its auxiliary equipment to make sure that the system is ready for operational use. Scheduled maintenance consists of the maintenance activities which are planned in advance, and which are accomplished according to a more or less rigid schedule. Troubleshooting is the process of identifying the source of malfunctioning in the equipment and then repairing or replacing the defective units or components.

"It is recognized that these categories of work, though logically separable, may be under way simultaneously in a computer center. Only when things are working well are the checkout and scheduled maintenance events completely foreseeable. In a case of trouble, checkout and diagnostic programs may both be at work in the computer, with preventive maintenance being done on certain units of the equipment at the same time."

Many aspects of the checkout procedure are fully automated in today's computers. "A systematic run-through must be made that will activate all (or nearly all) of the internal commands under various conditions. Included in the procedure will be programs to test tape and card units, indicator lights, printers, typewriters, and auxiliary memory. Most computer installations report that this run is accomplished by the technicians and not by the operators. This is presumably due to the fact that if something goes sour during the checkout, the technician must be called anyhow.

"The checkout procedure itself consists of inserting specially designed programs into the machine, observing the results, and taking action to meet prescribed machine criteria. These programs are run through many times, and their successful completion is usually accepted as sufficient evidence that the computer is operating perfectly.

"It seems that the number of checkout programs used by an installation does not have any direct relation to its size, but depends on the way the programs are constructed and also upon the number of different peripheral equipments to be included in the checkout. On the average, an installation has eight checkout programs. One installation used 25 checkout programs, while another with the same model computer uses only one. In the latter case, of course, many of the function tests have simply been combined into a single routine.

"The average time required for a checkout is one hour. Naturally this varies considerably from place to place. One computer center takes only 10 minutes to run the checkouts; another requires three hours.... A practical basis for this divergence in philosophy is found in the way the computer is used. A computer employed primarily for routine tabulating purposes does not have its capabilities exercised to any great

extent. The need for strenuous checking in such a case is much less than for a computer running elaborate telemetering problems which are programmed to take every advantage of the machine's capability."

Concerning the use of checkout routines, "About half of the installations report that they get through it over 75% of the time without trouble. Occasionally the computer won't run at all; the technician can't even put his checkout programs on it. Principal culprits accounting for this total loss of capability were power problems, failure of machine to read from card to tape, improper action of memory addressing circuitry, and (rarely) difficulties in the master clock timing. Technicians are not particularly disturbed by this situation, since the malfunction is usually isolated to a major unit very quickly."

A no-go checkout result does not necessarily mean that the system cannot be used; the system may be able to proceed with certain kinds of data processing. "Sometimes the computer runs through checkout perfectly, but when the real program to be computed is inserted, it doesn't work properly. This happens as frequently as once a month for some installations, and for others it occurs only once or twice a year. Generally this situation is attributed to the fact that the machine is not 'stressed,' or extended, as much by the checkout programs as it is by the money run. Also, some machines are pattern sensitive. That is, due to minor design imperfections, certain instruction and storage sequences which rarely occur will cause the machine to malfunction. It is for these reasons that the technicians find it necessary to modify their checkout routines and, on occasion, to originate new checkout loops.

"All of the computer installations visited use marginal checking. In fact, a majority of them claim that they can margin check over 75% of the main computer circuitry.

"An appealing feature of the marginal checking concept is its usefulness in detecting intermittent failures. Intermittents have always been a bugaboo to the maintenance man. To take care of an intermittent, he usually has to wait until the offending part fails completely, or else he has to accomplish wholesale replacement of units and components. Insofar as marginal tests catch intermittents, they are indeed a boon to the beleaguered technician. There seems to be very little documentation of the extent to which intermittents can be trapped in this manner, but most of the technicians interviewed were convinced that statistical studies would show considerable reduction of intermittents with a margin system. ...There is considerable agreement that marginal checking is needed for large machines that use enormous numbers of vacuum tubes. In the case of solid-state computers, however, a controversy is arising as to the necessity for marginal checking."

The established maintenance procedure was often modified to meet local conditions or to accomodate field experience. "All the maintenance managers interviewed had done some changing and tinkering with their checkout procedures. Generally, the changes were aimed at shortening the time

required, simplifying the routines, eliminating useless portions, increasing reliability, and arranging for better print-outs of results."

A discussion of peripheral equipment points out that mechanical assemblies often have more trouble than the main frame. Furthermore, a different kind of technical skill and fault location technique is required for this auxiliary gear. Installations may have from four to fifty pieces of peripheral gear, each requiring checkout and servicing. "Because of the greater amount of electro-mechanical elements in the peripheral equipment, it is not surprising that only four installations spend more than 30% of their routine maintenance time on the central computer."

Digital equipment imposes special requirements on the technician. "The extreme precision of relationships in the equipment, and their essential on-off nature, lead to a sharper definition of the problem to the technician. He cannot slur over the indication. He cannot get by on vague intuitions about circuit relationships, as a good many people do in troubleshooting other types of gear. The technician must structure the problem in terms of functional or logical interrelationships of the equipment rather than in terms of quantitative electronic characteristics." While troubleshooting "is a task requiring considerable abstract reasoning ability, since one must work within a complex problem framework which has tight symbolic restraints,...sophisticated knowledge of electronic functioning is not required of a digital troubleshooter.

"Most of the installations claim that the biggest limitation is that the (diagnostic) routine doesn't tell the technician where to look--it only shows the functional status of the computer, and still leaves the technician with the job of locating the bad part. And there are times, such as with power supply failure or input-stage breakdowns, when the diagnostic cannot be run through the computer at all. Diagnostics tend to be valuable only for certain types of troubles, and with other types are of no help at all. A repeated comment was that the technicians don't use the diagnostics unless they have to--the program that was in the machine when it broke down is usually a sufficient guide."

Other topics treated in the report relate to personnel problems associated with the selection, training, and supervision of the maintenance staff.

60. Dale, H. C. A., Gambling, Intelligence and the Training of Electronic Maintenance Personnel, Applied Psychology Unit, Cambridge (n.d.).

An experiment was conducted with 40 military maintenance mechanics to determine the relationship among the level of training, intelligence, and the use of relatively unsystematic fault-finding methods in maintenance of electronic equipment. Eighteen of these men always used one of the systematic troubleshooting methods demonstrated by the experimenter. Twenty-two took a gamble (i.e., took an action on the basis of

hunches rather than on the basis of a systematic approach) at least once. It was found that "intelligence determines not the hunches the man had, but whether he chose to be guided by them." Level of training had little effect. It was concluded that "the traditional method of training, in which fault-finding is looked upon as an exercise in applied electronic theory, will have to be drastically changed, if for no other reason than that these men will not be capable of assimilating electronic theory."

61. Fitts, P. M. (ed.), Human Engineering for an Effective Air-Navigation Air Traffic-Control System, Ohio State University Research Foundation, December, 1950.

(Note: This abstract is restricted to parts of the report dealing with man-machine function allocation.)

There are four alternative man-machine systems: (1) fully automatic control, (2) automatic control with human monitoring, (3) semi-automatic control supplemented by human performance of critical functions, and (4) primary control by human operators who would be assisted by effective data-analysis, data-transmission, and data-display equipment. The second system probably would not work well because humans are by nature poor monitors. In tasks that call for long periods of inactivity, humans have an almost universal tendency to become inattentive and bored and sometimes fall asleep. Even if the system were arranged to force the attention of the human monitor at the time of equipment failure, it probably would not be satisfactory. One premise assumed in considering this kind of system is that the human should be prepared to take over critical functions of air traffic control in case of emergency. But a man cannot make intelligent decisions in an emergency unless he has an adequate understanding of the traffic picture at the moment of the emergency and for a short time preceding it. Thus, the monitor must keep alert and thoroughly informed of the traffic situation at all times in order that he can take over in emergencies, but a monitoring system is one of the worst possible kinds of work situations for the human to stay alert in.

Although "humans are notoriously variable in their behavior under conditions of extreme stress,... there is some evidence to suggest that under lower load conditions a human, in some ways, performs better than does a machine." Human performance may be degraded under stressful conditions, but there is usually not a complete breakdown.

"Machines are by no means infallible, but in general they can be made to carry out specific functions with fewer errors than would be made by humans. This raises the question of whether safety should depend on human alertness and decision making or on automatic machines. Our answer to this is an unqualified assertion that the primary responsibility for safety should not rest on humans."

Taking these facts into account, "we suggest as an important working principle that checking, verifying, and monitoring equipment be devised that will make it impossible for any human in an aircraft on the ground to

violate basic safety rules, such as assigning two aircraft to the same block of space. This is the reverse of the commonly expressed idea that men should monitor machines. We are suggesting that machines should monitor humans.

"Humans appear to surpass present-day machines in respect to the following:

1. Ability to detect energy of certain wave lengths.
2. Ability to perceive patterns and generalize about them.
3. Ability to improvise and use flexible procedures.
4. Ability to store information for long periods and to remember relevant facts at the appropriate time.
5. Ability to reason inductively.
6. Ability to exercise judgment.

"Present-day machines appear to surpass humans in respect to the following:

1. Ability to respond quickly to control signals, and to apply great force smoothly and precisely.
2. Ability to perform repetitive, routine tasks.
3. Ability to store information briefly and then to erase it completely.
4. Ability to reason deductively, including computational ability.
5. Ability to handle highly complex operations, i.e., to do many different things at once."

62. Folley, J. D., Jr., A Study of Training Requirements and Study Prerequisites for Ordnance Maintenance of Army Ballistic Missile Digital Computer Systems, Army Ballistic Missile Agency, AIR-34-59-FR-214 Report, October, 1959.

"The most important outcomes of the study deal with problems of designing effective, integrated systems; with questions of training philosophy; with challenging the point of view that automated troubleshooting is the answer to effective maintenance; with suggesting and partially demonstrating the feasibility of making common practice a process that most design engineers would say is impossible of achievement; with preparing prior to the delivery of the hardware, troubleshooting procedures that will find virtually any malfunction in the system."

Three Army missile digital computer systems (Redstone, Sergeant, and Pershing) are critically examined. Findings and recommendations are organized under four headings: (1) broad-scope, (2) core skills and knowledges, (3) specific skills and knowledges for each system, and (4) prerequisites.

The three systems differ markedly with respect to checkout instrumentation. "The Sergeant system has almost completely automatic checkout and troubleshooting facilities. Troubleshooting within modules is done at the depot or factory. The decision-making part of troubleshooting is entirely removed from the technician....The Redstone, on the other hand, has no automatic troubleshooting features. The technician is given some maintenance aids in the form of the system tester, the component tester, and some test problems. The technician, however, must figure out almost every move. He must decide...what should be his next step in isolating a malfunction....The Pershing (has)...training requirements similar to those of the Redstone, although probably not quite so severe.

"It is fairly clear that neither of these extreme solutions is very desirable. In one case (Redstone) there is a good chance that the system cannot be maintained at all. In the other (Sergeant) the costs go up, and the system may still not be maintainable in the field because of logistics problems. Similar solutions on future systems are not likely to be any better."

The author chooses "integrated system development" as the best solution. "It requires acceptance of a new philosophy of system design--the philosophy that the system includes not only hardware, but maintenance and operating procedures, technical manual content and format, and training and selection requirements for personnel...that the maintenance procedures people and training people have an equal say in decisions about system characteristics, along with the hardware designers." Technical manuals should be reference works to be used by men trying to do specified jobs, rather than a collection of information with an unspecified or unclear purpose.

The author supports his position by detailed reference to field conditions in the three missile systems. An investigator attempted to solve a troubleshooting problem on the computer. The first step was to consult the equipment manual. Before the manual could be used, however, it appeared that the troubleshooter would need certain qualifications: ability to interpret logical equations and logical diagrams, a considerable facility in using some papers published by the computer manufacturer, and a knack for combining system specifics into a conception of troubleshooting strategy. After encountering these requirements, the investigator "raises a serious question whether it is realistic for the army to attempt to train personnel to maintain this system, or others with similar requirements, without providing troubleshooting procedures developed by experts on the system."

63. Glanzer, M. A., R. E. Corrigan, and R. A. Glaser, Retention and Retraining of Skills in Cross-Trained Personnel (U), Air Force Special Weapons Center, Technical Report 55-15, August, 1955 (Secret-Restricted Data; abstract Unclassified).

Air Force personnel trained in mechanical tasks were given orientation and practice on checkout tasks for electronic devices. During training they used special job aids, consisting of a special checkout procedure, that clearly spelled out what they were supposed to do. It was also designed to be a learning tool. The mechanics were able to learn how to carry out the tasks, and they appeared to know why they were doing them. "Why" was defined as the interrelationships among the various subtasks. Thus, to use an automotive analogy, they learned how to check out the ignition system and the carburetion system individually, and then the procedural aid showed them how the ignition system affected the carburetion system.

After a short training phase, the mechanics were tested on their proficiency (time and errors) in performing these tasks. Their scores were equal to those of Air Force personnel who had received several months' of intensive electronics training and whose average educational level and electronics aptitude were significantly higher. (The electronics specialists were originally selected on the basis of a high electronics aptitude, while the mechanical specialists were selected for high mechanical aptitude but low electronics aptitude. The mechanical specialists were alleged to have a generally lower average intellectual level than the electronics specialists.)

Two secondary effects were observed. First, the mechanical specialists demonstrated the classical "Hawthorne Effect" in being singled out as experimental subjects and being allowed to learn to operate electronics gear. "Operation of electronics gear" was regarded as being on a higher social-intellectual plane. Second, the regular electronic specialists evidenced a strong desire to obtain the special job aids in lieu of the conventional manuals they had been using.

64. McGrath, J.J., A. Harabedian, and D. N. Buckner, Review and Critique of the Literature on Vigilance Performance, Human Factors Research, Inc., ASW Technical Report No. 1, December, 1959, 100 pp.

In addition to reviewing the literature on vigilance, this report describes various psychological theories of vigilance performance and presents an annotated bibliography of vigilance studies.

Vigilance can be measured by signals missed, by signals erroneously reported, and by response latency. Performance shows a rapid decrement in efficiency, but stabilizes with the first 10 to 30 minutes on a regular watch and may show an end spurt if the end of the watch is known

by the observer. Various environmental conditions, display and signal characteristics, and physiological factors can enhance or reduce vigilance; individual differences in susceptibility are large. There are several procedural conditions that can reduce the amount of vigilance degradation; presentation of many artificial signals when the real signals occur infrequently, scheduling of frequent rest periods, use of multiple observers, giving special incentives, and providing immediate knowledge of results.

65. McGraw-Hill Book Company Technical Writing Division, Design Factors for Aircraft Electronic Equipment, WADC Technical Report 56-148, December, 1956.

This is a general manual for the designer of military airborne equipment, with emphasis on maintainability-related items. Comprehensive sections are devoted to reliability analysis and to electronic, mechanical, and environmental design factors. The maintenance chapter mentions the principal variables in testing, accessibility, and equipment coding. Coverage is given to personnel safety items: interlocks, high voltage jacks, insulated controls, capacitor discharge devices, etc.

66. Miller, R. B., Common Job Components and Transfer of Non-Specific Habits in Electronics Line Maintenance. Part II: Some Theory and Hypotheses for Transfer of Training of Non-Specific Habits in Line Maintenance Jobs, AFPTRC Project 7709 Report, January, 1955, 34 pp.

Suppose you have a group of line mechanics for the Q-24 and you want them to learn another equipment such as the A3A; what kinds of transfer effects can be expected from one equipment to another? Considering superficial familiarity, the "Q-24 men could talk a better electronics game, and thus be more impressive to their supervisors and instructors ...but in actual job skills and performance it is at least possible that present Q-24 and K-2 line mechanics would be little better off than a group of controls." In general, "transfer effects would be either negative and transitory or non-existent."

A theoretical analysis of the transfer mechanisms encountered in non-specific job similarities is presented. The surrogate or implicit stimulus-response is a central concept; when organized into a pattern, these implicit relationships seem to filter out irrelevant material and reduce interference effects.

At least seven factors could yield positive transfer from one line maintenance job to another:

1. Learning what to search for in the work environment, including job purposes, physical cues, and symbolic cues

2. Enhanced distinctiveness of essential job cues

3. Habit patterns for noting and remembering information

4. Concepts of signal flow

5. Method for troubleshooting

6. Work methods

7. Use of checklists as performance guides and as supports for learning optimal elements of job behaviors

"In general terms these factors can accelerate learning to maintain a new equipment insofar as they provide directly usable implicit models for behavior and in reducing the 'learning duties' characteristic of the novices interaction with training materials and procedures."

67. Miller, R. B., et al., Survey of Human Engineering Needs in Maintenance of Ground Electronics Equipment, RADC Technical Report 54-31, February, 1954, 274 pp. and Appendix.

Observational, interview, and questionnaire data from six Air Defense sites were directed to the definition of maintenance problems on ground electronics equipment. Seventeen problem areas emerged: (1) accessibility; (2) presentation of technical information; (3) test equipment; (4) working conditions; (5) environmental effects; (6) safety; (7) component size; (8) power problems; (9) color-coding of equipment; (10) warning indicators; (11) cable connectors; (12) panel controls and meters; (13) circuit-switching arrangement; (14) preventive maintenance; (15) troubleshooting; (16) reliability; (17) supply. Specific illustrations and case examples are developed for each of the problem areas, and lists of research problems are given.

68. Miller, R. B., J. D. Folley, and P. R. Smith, A Comparison of Job Requirements for Line Maintenance on Two Sets of Electronic Equipment, Air Force Personnel and Training Research Center, Technical Report 54-84, December, 1954, 17 pp.

The "equipment-demands" form of analysis originated by Miller was applied to the Q-24 radar and to the K-1 bomb-nav system to determine the communality of job activities for the two systems. It appears that while many individual behaviors (e.g., reading a gage, accomplishing a screwdriver adjustment) are practically identical for the two equipments, real differences appear at the knowledge, judgment, and procedural levels. This finding suggests the possibility of establishing broad inter-system similarity at the procedural level, so that troubleshooting and other complex tasks can be more transferable from one equipment to another.

69. Miller, R. B., and E. B. Slebodnick, Research for Experimental Investigation of Transferable Skills in Electronic Maintenance, AFPTRC Technical Report 58-2, January, 1958.

Two experiments were conducted on transferable skills in electronic maintenance. The first dealt with specific and nonspecific factors, the second with troubleshooting principles.

Experiment 1 used 24 male high school seniors divided into four groups on the basis of intellectual level. The Search Group was given pre-training on how to filter relevant from irrelevant information from job instructions and maintenance diagrams. The Troubleshooting Group was taught three general rules of troubleshooting. The History Group, essentially the control for the Troubleshooting Group, was given a brief introduction to the history of electronics. The Search Control Group worked with the same job instructions and diagrams used for practise exercises in the training of the Search Group, but they were not taught "search" principles.

Following the pre-training, all subjects were given specific training on checking, adjusting, and troubleshooting a single-chassis Hi-Fi television receiver, a dual-chassis TV, and an audio frequency signal generator.

The results gave positive answers to the following six questions:

1. Does learning what to search for in complex stimulus environments aid in learning and retention of a task?

2. Does learning of general problem-solving principles in a relatively abstract practice environment transfer to specific task situations when the subject may have the option of memorizing and applying a set of routinized prescriptions as an alternative to the application principle?

3. Will different measures of retention have different effects in experimental and control conditions?

4. Do different non-specific skills affect performance of specific tasks differently?

5. Does spontaneous development of non-specific transfer of training habits occur in the course of job experience, without formal training in such habits?

6. Does level of intelligence have bearing on the generalization of non-specific habits to specific situations, and are there interaction effects?

70. Nickels, J. B., "Using the Human Element to Predict Equipment Maintainability," in F. L. Ankenbrandt (ed.), Electronic Maintainability, Vol. 3, Reinhold, New York, 1960.

The Diagnostic Ability Test is described. In its original form, the test consisted of 17 performance items ("mount the 1000-ohm resistor on the board") and 153 verbal items ("kilocycle is to what as milliampere is to current"). By means of item discrimination statistics, engineering re-

view, and correlation of item performance with AFSC skill level, the test has gone through several stages of refinement.

Once the DAT is available, it is possible to get test scores and actual "time-to-fix-it" scores from contract engineers and Air Force personnel and thus establish "specification graphs" or ability bands for a certain class of equipment. Such a band might, for example, include 95 per cent of the people at the AFSC-7 level; questions regarding the proficiency overlap between this group and, say, the contractor engineers can then be investigated graphically. An extension of the method occurs when an equipment has been maintained only by company engineers; from performance data on them and a study of the relevant specification graphs for Air Force people, predictions can be made of the maintenance times to be expected if Air Force personnel had to do the job alone.

A positive correlation has been observed between DAT scores and individual maintenance performance on the AN/FST-2 Data Transmitting Set.

71. Peterson, R. O., and E. M. Jones, Core Training for Electronic Maintenance: Principles and Techniques, AFPTRC Technical Memo 57-2, November, 1957, 21 pp.

"A job-oriented approach was followed in deriving core training. Training content was identified through an analytic study of maintenance activities. The activities were analyzed to identify skills and knowledges actually necessary to perform them, and which were common across maintenance positions. A substantial group of core skills and knowledges emerged. They were closely related to the conduct of maintenance, and quite different in character from the 'fundamental technical knowledge' content of typical initial maintenance courses."

Two classes of transfer mechanisms are distinguished. The identical elements class relates to specific equipment details: which tool to use, how to locate a part, how to attach a meter, etc. Transfer to the job situation then becomes primarily a matter of remembering these activities until the job situation calls for them. A second, more complicated mechanism might be called transfer of common principles, precautions, and performance rules.

72. Rigney, J. W., "Improving Trouble Shooting by Training," in F. L. Ankenbrandt (ed.), Electronic Maintainability, Vol. 3, Reinhold, New York, 1960.

Troubleshooting is not now emphasized in military and industrial training schools, for several reasons: expense, relative ambiguity of the subject matter, and curriculum inertia which perpetuates old methods of training. But suppose that troubleshooting is to be taught explicity; what are the most promising techniques to exploit?

"First, it is clear that trouble shooting skill can be improved by giving technicians...highly enriched practice in solving symbolic trouble shooting problems. This practice gets at the crux of the trouble shooting

task. To be sure, it omits the actual equipment, the problem of finding test points in often confusingly arranged components, and the very important task of employing test equipment properly. However, we maintain that unless the technician is able to trouble shoot efficiently at a symbolic level, it would be of little avail to him to be skilled in these other aspects of trouble shooting.

"Secondly, this approach to trouble shooting is the most efficient one that we know of as yet. The technician is given a great deal of practice, with continual feedback, in a relatively short period of time, because there need be no waiting for repair of equipment, insertion of faults, or peaking up of equipment in between problems. The paper-and-pencil trouble shooting problems can be reproduced en masse, and can be administered to large groups of technicians at a time. This is not possible with live equipment.

"The current fashion in maintainability seems to be the development of automatic or semi-automatic checkout and fault-locating systems. This, coupled with the modularization of equipment, will go a long way toward providing what one investigator has called the necessary discreteness of units and of checking sequences. These features unquestionably are necessary, in view of the order of complexity one finds in today's systems. Without them, the performance of corrective maintenance might be impossible. However, it would be an error to suppose that trouble shooting can be removed completely from human hands. There is a great danger that the appealing concepts of automation will obscure the critical need for improving trouble shooting proficiency of the technicians in the field, yet these men will continue to be responsible for keeping these systems on the air."

73. Shriver, E. L., Determing Training Requirements for Electronic System Maintenance: Development and Test of a New Method of Skill and Knowledge Analysis, HUMRRO, Technical Report 63, June, 1960, 100 pp.

"In the present study, methods were developed that were designed to derive, from a system's preproduction information, a set of data that would be sufficient for the initial establishment of a complete training program for repairing and operating that system. The development of these methods, their application to an existing radar system, and the testing of the repair proficiency of men trained in the content derived by the methods are described in this report.

"The two basic assumptions that guided the development of the FORECAST methods of analysis are:

(1) Any job, including those involving logical reasoning, may be described in terms of certain cues which a man receives through his senses, and respones which he makes to accomplish his job.

(2) Learning the cues and responses and the cue-response association which describe the job equips the man for doing his job better than learning any other type of information."

The specification of cues and responses for the operator task are relatively straightforward because the equipment (hopefully) has been designed so that required responses are connected with distinctive display conditions. Task definition for maintenance is more intricate, and a specially modified cue-response correlation scheme seems to be necessary. Essentially, the method proposed divides the system into four conceptual levels: (1) channel, (2) channel segment or "gray box," (3) tube chain, and (4) part. Each level has its own cue. Thus, if a malfunction occurs, symptom cues are related to the block diagram, gray box waveforms to particular check points, resistance readings at terminal points of tube chains, and resistance readings across parts.

An experimental training program was devised using the cue-response philosophy. Tolerances and diagrammatic indications for each level of response were set up to facilitate learning. The experimental course required 12 weeks of training. The performance of graduates of this course was compared with that of a similar group which had taken the conventional 30-week training sequence. The criterion was a nine-day performance test on portions of the M33 Anti-aircraft Fire Control System. No significant differences in proficiency were found between the two groups, with the conclusion that the experimental method is equally effective in terms of final skill and over twice as efficient in terms of training time.

74. Spector, P., A. D. Swain, and D. Meister, Human Factors in the Design of Electronics Test Equipment, RADC Technical Report 55-83, April, 1955, 121 pp.

Electronic maintenance is an information-handling situation in which three components interact: the maintenance man, his test equipment, and the equipment being maintained. Differences in ability among Air Force 3, 5, and 7 level (i.e., semi-skilled, moderately skilled, and highly skilled) technicians are considered with relation to test equipment use. Several proposed solutions to the test equipment problems are examined, and it is concluded that human engineering design of test equipment, as suggested in the report, was the most adequate solution. The use of strictly go/no-go test equipment was rejected, primarily because of limited maintenance flexibility and ancillary requirements for a greater number of test devices, more complex test equipment circuitry, and related training and logistics problems.

The logistics problem of getting equipment replacements is partly due to non-ruggedized test equipment as well as lack of human engineering design to minimize damage.

Some of the inadequacies of auxiliary aids, such as technical orders, maintenance guides, schematics, and check lists, are listed, and human engineering recommendations are given on written aids for the technician to use with his test equipment.

The data in this study were collected by activity analyses and task-structured interviews at a large number of field communication and

control sites. A ten-stage work cycle was used to structure the observations:

1. Selecting test equipment
2. Locating test equipment
3. Transporting test equipment
4. Attaching test equipment to prime equipment
5. Setting up test equipment
6. Determining test equipment accuracy
7. Identifying test points
8. Reading test equipment information
9. Interpreting test equipment information
10. Securing test equipment

75. Swain, A. D., Maintenance Diagrams for Preventive Maintenance of Ground Electronic Equipment: Phase I Recommendations for Determining Their Need, RADC Technical Report 56-141, November, 1956, 170 pp.

The goals of this project were "(1) to determine what maintenance information should be presented in diagram (graphic aids) form for preventive maintenance operations of ground electronic equipment and (2) to decide the best method of presenting this information in diagram form."

A study of the information needed by the technician at various stages of the work situation yielded a baseline for evaluating current preventive maintenance diagrams. It was discovered, first, that much of the needed information was not found in current diagrams; second, that extraneous or job-irrelevant information was frequently presented in the diagrams; and third, that the form of presentation used in the diagrams was not suitable for apprentice mechanics. "This disparity between diagram needs and current diagram design led to the conclusion that several models or types of diagrams, called Preventive Maintenance Diagrams, should be developed specifically for preventive maintenance operations."

76. Swain, A. D., Maintenance Diagrams for Preventive Maintenance of Ground Electronic Equipment: Phase III-Final Report, RADC Technical Note 57-379, 14 pp. and Appendix.

This report summarizes the work on the Preventive Maintenance Diagram project. It describes the 16 basic types of Preventive Maintenance Diagrams (PMD's) developed, and the two scientific reports which tell when they are needed, how to design them, and what potential value PMD's should have for preventive maintenance operations.

77. Swain, A. D., Test Measurement Requirements for 1960-62 Ground Electronic Equipment: Phase I. The Need for New Types of Test Devices, RADC Technical Report 58-22, March, 1958, 63 pp.

A review of prime and test ground electronic equipment developed in 1958 for use in the early 1960's revealed that most existing test measurement practices would be continued. Data on the use of test equipment by

Air Force Specialty Classification 3- and 5-level maintenance mechanics at Airways and Air Communications Service maintenance sites showed many liabilities in existing test equipment. The following difficulties are anticipated.

Test devices have limitations in operability. Examples cited show complex set-up procedures, confusing display-control arrangements, error-likely situations, hazards, dangers of damage, and requirements for numerous items of test equipment to obtain elements of prime equipment information.

Test devices frequently present information not immediately compatible with the maintenance action required. In many cases the mechanic must decode, compute, interpret, and then decide what to do rather than obtain "command-type" information. Except for single-purpose, or built-in, test equipment, there may not be an entirely satisfactory solution to this problem.

There is also evidence of low transferability of skill in the operation of different test sets at a site; even though the sets may perform the same maintenance function.

78. Swain, A. D., G. R. Purifoy, Jr., and E. B. Slebodnick, Maintenance Diagrams for Preventive Maintenance of Ground Electronic Equipment: Phase III. Recommendations for their Design, RADC Technical Note 57-379, October, 1957, 86 pp. and Appendixes.

This report contains (1) recommendations for designing 16 basic Preventive Maintenance Diagrams (PMD's) recommended for inclusion in the Air Force Preventive Maintenance Instructions Technical Order series, (2) a description and analysis of a mailed questionnaire evaluation by 127 maintenance mechanics of 22 prototype PMD's, (3) statements suggesting the most suitable use of these graphic aids which were designed especially for preventive maintenance operations on ground electronic equipment, and (4) examples of the 16 basic types of PMD's.

A previous report on the same project, RADC TR 56-141, tells (1) how to determine when a PMD is needed, and (2) what information should be included in the PMD.

The present report concludes by predicting that if future Preventive Maintenance Instructions Technical Orders incorporated PMD's, these diagrams would be acceptable to maintenance mechanics, and help reduce maintenance errors, injury to personnel, damage to equipment, time taken to perform preventive maintenance operations, and the amount of on-the-job training required before an apprentice mechanic can reliably perform these operations without supervision. Finally, it predicts that acceptance and use of the written instructions plus graphic aids by all maintenance sites would increase the standardization of preventive maintenance operations. These predictions are based partly on the results of field evaluation of the PMD's and partly on a systematic

analysis of preventive maintenance information requirements for graphic aids for apprentice mechanics. This analysis, reported in RADC TR 56-141, preceded the development of the PMD's and associated recommendations for their design and use.

In addition to specific layouts for the 16 types of PMD's, the report provides general design recommendations on the following topics: photographs versus drawings, types of drawings, symbology and its limitations, placement of PMD's in the written technical orders, size of the PMD's, size of objects and printing on the PMD's, durability of the PMD's under typical field conditions, use of color, use of caution and warning items, symbols showing direction of movement, labeling, call-outs, and call-out lines, and learning of diagram symbols.

One hundred and twenty-seven maintenance mechanics of all skill levels from 13 AACS sites examined 22 prototype PMD's and furnished questionnaire responses regarding them. They were asked to assess the degree to which each PMD fulfilled one or more of the following five purposes: (1) reducing maintenance errors, (2) injury to personnel, (3) damage to equipment, (4) time taken to perform preventive maintenance operations, and (5) the amount of on-the-job training required before an apprentice (AFSC 3-level) mechanic could reliably perform the operations without supervision. The over-all response was highly favorable. For every ten mechanics participating in the evaluation, about six replied favorably, one unfavorably, and three omitted the question, gave irrelevant responses, or felt the PMD in question was not applicable to a specific purpose. Study of the irrelevant replies revealed that the individuals responding in this manner did not comprehend the limitations and objectives of the PMD's. This finding suggests that before graphic aids are introduced, the personnel who will use them must be trained briefly on their purpose and application.

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VI. SPECIFIC CHECKOUT SYSTEMS

79. Brock, P., and S. Rock, "Problems in Acceptance Tests of Digital Computers," J. Assoc. Comput. Mach., Vol. 1, 1954, pp. 82-87.

The development of tests to exercise the computer, and the determination of the acceptable number of errors for quality specifications are discussed.

80. Brown, D. T., Error Detecting and Correcting Codes for Arithmetic Operations, IBM Data Systems Division, IBM TR 00.718, May, 1960, 15 pp.

Coding schemes of the $A_n + B$ form are described, where n is the number to be communicated and A and B are integers. Sufficient conditions to achieve single-error detection and correction are stated and several theorems are proved on "smallest values" and "residues." Minimum-length codes for single-error correction in different number bases are given in tabular form.

81. Daggett, N. L., and E. S. Rich, Diagnostic Programs and Marginal Checking in the Whirlwind I Computer, Digital Computer Laboratories, Massachusetts Institute of Technology, March 26, 1953, 9 pp.

In the Whirlwind Computer "it has been found that marginal checking vastly reduces the machine failure into 4 series of test programs, each of which thorougly exercises a different section of the machine which is used in the marginal checking procedure. Marginal checking cannot prevent intermittent and total failures caused by shorts and opens. These are isolated by built-in checking features, diagnostic programming, signal tracing and operator experience and ingenuity. These methods are greatly facilitated by a special program control which allows a periodically repeated test program to be stopped at an arbitrary point to study indicator lights and signal wave forms."

82. Eldred, Richard D., "Test Routines Based on Symbolic Logical Statements," J. Assoc. Comput. Mach., Vol. 6, No. 1, January, 1959.

A philosophy for the construction of test routines for the checkout of computers is stated: "In order for the successful operation of a test routine to guarantee that a computing system has no faulty components, the test conditions imposed by the routine should be devised at the level of programmed orders. Therefore, it seems that the proper approach to writing test or maintenance routines is by way of the logical diagrams of the system, and not the list of machine orders. This is the only way in which all conditions of operation of each logical function can be uniquely and completely defined and all logical components within each logical function can be made to perform the task to which they are assigned. Orders can then be programmed to present all conditions, and further orders can be programmed to detect improper performance of the logical functions, thereby producing a minimum program which tests and detects failure in each logical component in the system." The article is devoted to

the construction of a routine which can itself construct a test routine; the program was used to construct a test routine for the Datamatic 1000. "This program has been used successfully during the debugging and production stages of the Datamatic 1000 and is now being used in the field as the principal maintenance routine for the Central Processor."

83. Electrodata Division of Burroughs Corporation, 220 Basic System Preventive Maintenance, Field Engineering Standard Practice Instruc- No. 25.20.0313, September 2, 1960 (used with 220 Test Routines, Vol. 2, No. A65535.)

These documents are intended for use by field personnel who service the 220 computer. The maintenance approach is that "The individual Diagnostic Tests should be used as an aid in locating machine malfunctions, and as Standard Performance Tests on the unit level.

"Throughout this volume, the programming techniques are as simple as possible, consistent with effective, efficient testing. All Data Processor tests are coded in short iterations to simplify understanding of the coding. Lock up and re-entry points have been provided to save trouble-shooting time. Simple, logical flow diagrams, informative operating description, instructions, and a complete table of errors are provided for each test. In most cases, the address of the error halt is a direct index to the detailed program instruction list.

"In keeping with the philosophy of simplicity of operation, all error expression in this volume is through keyed Halt orders. Admittedly, there are a few cases where a printout would have been more desirable. These cases, however, were few and far between, and would have involved a confusing printout iteration which would have been no more informative than the Halt order.

"One of the advantages of using Halt orders for error indication is that a handy listing of possible Error Halts can be included with each test. Through this listing, the operator can immediately determine where in the test the failure occured and the condition of all toggles and registers are generally undisturbed. In the majority of cases, the address of the Error Halt is a direct index to the detailed program instruction list.

"In all tests, excluding memory tests, the Error Halt is followed by and unconditional branch to that portion of the test which causes the error to be detected. This allows the operator to visually observe the error occurrence. If the return pass does not fail, the test will continue in sequence. Lockups are provided, using Program Control Switches, to repetitively re-execute desired sections of the tests for the purpose of more conclusively isolating a failure. These optional lockup features are specifically outlined in the write-up associated with each test."

Detailed error explanations are illustrated: "All errors are expressed through keyed HALT (00) orders, of the format .00nn00aaaa, where nn = error key, and aaaa = either re-entry point after error, or address of memory location which failed.

"In error Halts related to the memory section, the contents of the 'A' or 'R' registers have significance in relationship to the error. A note to this effect will be found in the error table associated with the Halts which have this feature.

"After an error has been detected, and the Halt executed, the case which caused the failure will be tried again, and, if successful, the routine will continue in sequence. If the repeat is not successful, the Halt will again be executed. In the case of the memory section, the routine continues in sequence, after a Halt.

"If is is desired to lockup on a failure, Program Control Switch #1 should be set at the time of the error Halt. This lockup will suppress the error Halt, and allow continuous operation on the failing case."

84. Graney, E. P., "Maintenance and Acceptance Test Used in MIDAC," J. Assoc. Comput. Mach., Vol. 2, 1955, pp. 95–98.

The general MIDAC test criteria are:

"1. Severe operating conditions for the computer must be produced.

2. A sufficiently large set of random numbers must be operated upon.

3. Elements of the computer must assume all possible states and be checked."

For arithmetic checks, two kinds of techniques are useful: (1) the repetition of a "sample" problem, and (2) the generation of a pair of random numbers, numerical operation on the numbers, and subsequent comparison of results.

85. Grems, M., R. K. Smith, and W. Stadler, "Diagnostic Techniques Improve Reliability," Proceedings of the Western Joint Computer Conference, February, 1957, pp. 172–178.

This paper investigates diagnostic means to improve computer programs. "The trend toward completely planned program-controlled diagnosis of errors can be illustrated by considering three levels of diagnostic techniques according to their degree of automaticity:

1. Manual techniques use program tests to cause a machine STOP in case of an error. Minimum planning is expended in the hope that a STOP will not occur.

2. Semi-automatic techniques prepare a logical pattern of program tests and record data before a machine STOP. Planning is required to prestore useful information before the occurrence of an error.

3. Automatic techniques require extensive planning, as part of a complete system, to circumvent a machine STOP. A programmed method is necessary to report trouble and still get results."

Manual methods are also described. "Manual diagnostic techniques are not new to computing practices but are an outgrowth of the old familiar check list. A check list is used at progressive stages during hand computing to explain progress and to ensure that completed results are similar to anticipated results at each stage. The designers of computers recognize this need for a check list, and include machine operation codes for conditional and unconditional STOPS and TRANSFERS; e.g., STOP, HALT, MS (Manually Selective Stop), EJ (Equality Jump) and TRO (Transfer on Zero). The early computer programs would be unreliable without these operations codes and an accompanying check list.

"In a manual diagnostic routine the common practice for using conditional and unconditional STOP and TRANSFER codes is to include a STOP for any questionable situation. Then, when the STOP is executed, this manual procedure follows:

1. Manually copy all information from the console panel.

2. Dump or trace that portion of storage containing the STOP instruction.

3. Scrutinize carefully (on or off the machine) the instructions and the console information, hoping to isolate the error.

4. Decide on a corrective measure.

5. Employ the corrective measure in the program."

For certain complex interpretations, a semi-automatic approach may be indicated. "Semi-automatic diagnostic techniques include not only the detection and isolation of errors, but also the recording of comments and pertinent data by the program. They are a direct outgrowth of the manual techniques and a stepping stone to a fully automatic routine. The recording of comments by the trail, when something is amiss, assures the engineer that unusual circumstances are recognized and therefore increases confidence in the reliability of results. This ability to isolate errors automatically and record pertinent information is a big step forward in diagnostic techniques. It assures that spot-checking is taking place during computing and

is essential to computing and coding systems where relocation and storage assignment are delegated to the system itself. Currently, there are a number of successful diagnostic routines using these techniques for such computers as International Business Machines Model 701, 704, and 650; for Remington-Rand Models 1103 A and UNIVAC; and for the Bendix G-15.

"Semi-automatic techniques are used in the algebraic computing system, BACAIC. When the BACAIC IBM 701 program detects an error, the program prints the reason for the error and suggests a corrective measure. It also prints a minimum of information to pinpoint the actual storage location of the error and the relative location of the computing in the problem.

"The preceding example illustrates that the second level, semi-automatic diagnostic routine leaves a train of problem progress. Reliability is promoted thereby because rather permanent evidence is available which shows the actual path of the calculation. Furthermore, intermediate answers allow hand-calculated checks upon the methods or the final results at any convenient time when added assurance is felt necessary. However, the routine in the example is termed semi-automatic because analysis of the trail and any corrective actions are performed at manual speeds after a machine STOP. Any such manual procedure is subject to fumbles, errors, and costly delays even for small programs. More advanced program-controlled techniques are necessary to improve reliability as problems become very large and thereby multiply the costs of manual machine procedures. The confusing mass of detail concealed in an integrated computing system prohibits any person or group of people from tracing trouble in the earlier fashion of STOP, copy control console, consult check-list, consider locations in storage, dump large portions of storage, and then retire gracefully for analysis. These slow procedures impede communication between man and machine and are contrary to more sophisticated thinking as expressed in the deluge of literature on 'automatic programming'."

The progress in achieving automatic diagnosis is conveyed by presenting a routine that runs down trouble on its own; when the routine finds evidence of the exact trouble, it stops and displays its results in printout form.

86. Hart, E. D., "Maintainability Design for the Airlines Aironics Market," in F. L. Ankenbrandt (ed.), Electronic Maintainability, Vol. 3, Reinhold, New York, 1960.

Compared to the military service, the airlines generally pay far less for their original equipment, use it far more, and yet have fewer maintenance problems. Among the reasons for this are the motivation, experience, and stability of the technician force. Hypothetical curves show a drop in maintenance costs and a rise in maintenance quality as personnel experience increases.

Simplicity of procedure is another favorable maintenance feature. The airlines technician can usually modify his corrective procedures to suit local conditions, and he can apply his experience to preventive maintenance as well. Detailed maintenance records are a central job aid, and file cabinets of every piece of equipment are kept right next to the maintenance bench. It is stated that one clerk in one airline keeps records on most of the electronic equipment in over 100 planes and publishes monthly work summaries. Contrast this efficient system with unwieldy military reporting schemes!

Accessibility is a major equipment attribute which the airlines favor, but a blind principle of "make everthing accessible" is not followed. Certain service adjustments, for example, are made inaccessible to prevent inexperienced people from making adjustments. Modular construction of equipments is seldom justified at present because of the high cost of replacement modules; the technician usually has to troubleshoot down to the failed component.

87. International Business Machines, Development and Evaluation of Systems Reliability and Maintenance Techniques (U), Final Report ECPX0009, January 1, 1959, 146 pp. (Secret).

This report discusses means for improving reliability and performance, rather than maintenance techniques.

88. Johnson, R. D., Nike Hercules Computer Monthly State and Dynamic Field Test Procedures and Requirements (U), Bell Telephone Laboratories, July 24, 1957, 28 pp. (Confidential).

A list of field test for an analog computer installation is given.

89. Kovit, B., "Data Acquisition Link Makes or Breaks Checkout Designs," Space/Aeronautics, Vol. 34, No. 4, October, 1960, pp. 215-219.

"Even the most sophisticated checkout system is only as good as the data it is given to work on." Methods of assuring good test data samples include frequency counting, which is simple to instrument because one has to count against a time base; and voltage measurement, in which it is necessary to monitor both noise and voltage level and then pass through a voltage-frequency conversion before making a go/no-go decision.

Direct cables are almost universally applied in missile test sequences; these cables provide test confidence and relative freedom from external interference. On the negative side are cross-talk problems, outside exposure, and rough treatment. "It was certainly no wonder that, on a missile like the Martin Matador, over half of all abort-causing failures should occur in either the instrumentation or the checkout cabling." Furthermore, if signal levels are extremely low, amplification is required. It is speculated that "future systems will

eliminate these amplifiers wherever possible and use digitizing elements as close to the raw data source as possible."

Air-link checkout problems are similar to those of telemetry. Again, immediate digitizing is proposed for a radio link. For the future, a single universal test center could, by coded air data links, replace large numbers of the special (but overlapping) test equipments now in use. Such a master central scheme could be closely interleaved with the computer in the missile itself, since using the prime equipments' own computer may be "the coming thing in missile checkout."

Test logic for the Minuteman missile is briefly reviewed. Outstanding features are (1) the extraordinary care taken to prevent cabling difficulties and (2) a "hot storage" of recent calibration tests. This storage is used when instantaneous calibration data are temporarily unavailable; the sequence does not just stop, but proceeds on the basis of the most recent stored tests.

90. Laporte, H. R., "Human Factors Analysis of an Automatic Checkout Device," paper presented at the Sixth Annual Army Human Factors Engineering Conference, Ft. Belvoir, October, 1960, 13 pp.

Automatic checkout equipment can save time, provide reliable measurements, reduce skill requirements, perform self-tests, and record test results. However, a human operator will still be necessary to apply power, load the program, and initiate the test sequence. Technicians will also perform corrective maintenance on the prime equipment and on ACE itself.

Observation of a particular checkout device in action showed that certain operating difficulties existed: e.g., controls and displays were mixed, insufficient status information was provided, interlocking facilities were inadequate. Panel redesign eliminated, to a large degree, the previous inadequacies and provided a more satisfactory checkout capability.

91. McNaughton, R. A., "Automation for Quality Control Testing of Electron Tubes," <u>IRE Trans., Reliability and Quality Control</u>, PGRQ3-9, September, 1960.

"Prior to the mid-Forties most electron tubes were production- and quality-tested on an attributes (go-no-go) basis only...sample sizes were moderate and statistical paper work...a minimum. Since that time quality-control testing has increased by leaps and bounds under the pressure for high reliability, performance, and uniformity... additions to the quality-control workload have resulted in the addition of statisticians, clerks and typists to the personnel of the quality sections, an increase in the number of test sets and operators and an increase in the number of life-test sockets to accommodate the life requirements...an appreciable portion of the tube manufacturing cost is involved in the quality-control testing and statistical evaluation procedures.

"In an effort to discover ways and means for curtailing the increasing cost of testing and the time-lag required for lot release, the entire quality control process was reviewed to determine where automation could produce the desired results.

"Since many of the measurements contributing to the increased cost and time-lag are made on the vacuum-tube-bridge test sets, and these measurements provide the data for the statistical work, it was concluded that automation of the bridge measurements and statistical computations would provide the best possibility for cost reduction.

"A test set (was) developed which performs many of the tests automatically. The set provides digital data output for each test on each tube in punched tape, reads out the tape, and prints a copy of the punched data. The punched tape is then fed to a computer which analyzes the data for the entire sample and prints out the answers for those statistical factors such as lot means, standard deviations, per cent deltas, etc., required for the attributes-variables acceptance criteria for lot acceptance. The test set is designed to perform those static and dynamic tests normally performed on a vacuum-tube-bridge test console. It has twenty test positions and will measure and record ten different characteristics on dual section tubes. Provisions are included for manually feeding test data from other equipments into the punched tape for analysis by the computer as desired.

"The twenty test positions provide the necessary steps for making the following tests on dual-section tubes: filament, plate, screen-grid, control-grid, and heater-cathode-leakage currents under dc conditions; dc or ac emission; transconductance; plate resistance; and intermediate and cut-off-bias plate currents. In addition, power output and/or ac amplification tests may be substituted into the test cycle as required by deletion of other tests.

"To facilitate data processing, the tests are sequenced so that those having values normally distributed occur at fixed steps in the test cycle. Any test may be omitted from the test sequence by wiring in a skip function on the program board. Tests at a changed heater voltage condition such as reduced-heater plate current, transconductance or power output and high-filament grid current are made by first testing the tubes at normal conditions and then rerunning them in the same order under the changed condition and with all tests except those desired skipped out."

The manual operations that must be performed in conjunction with the tester are then described and illustrated in a step-by-step manner.

"The control section of this set contains many other provisions of most importance to the proper timing and flow of information through the system.... A manual-automatic switch is provided which, when in

the manual position, deactivates all the automatic test-cycling circuits and permits manual indexing through the test cycle by pressing the index switch for each test.

"By proper arrangement of the test sequence, data reduction procedure, and computer programming, it has been necessary to prepare only three computer programs in order to handle the great majority of tube types.

"These include one program for the single triodes, diode-triodes, amplifier pentodes and diode-pentodes; and one for the dual triodes, triode pentodes, and duo-pentodes; and one for the power triodes and pentodes and several special purpose types.

"Computations made by the computer include sample averages and standard deviations for all normally distributed characteristics; calculation of amplification factor, when required, from the GM and RP readings for each tube; per cent deltas with change of filament voltage or over time; and the number of rejects for each characteristic. These calculation results are all printed out for immediate use.

"Overall accuracy is within 1 per cent for dc measurements and within 2 per cent for ac.

"In conclusion, the development of the automatic recording test set has provided a means for accumulating the vast amounts of test data for electron tubes demanded by current quality control techniques in shorter time, at less cost, at better accuracy, and at a reduction in the demands on the test set operator whose prime requirement has been reduced to one of mechanical dexterity. Also, it has provided the means for obtaining a great amount of additional information about tube quality past and present at the cost of a slight increase in testing and computer time.

"It is definitely a major step toward automation of the test function in the manufacture of electron tubes and an assist in holding or reducing testing costs in spite of the ever increasing demand for more testing and statistical computations on the test data."

92. New York University, <u>Lecture Notes for the Design Course in Automatic Electronic Test Equipment</u>, Vols. 1 and 2, August 29-September 2, 1960, 352 and 205 pp.

The purpose of the course was to acquaint designers with a variety of techniques being applied to checkout systems. Several checkout arrangements were described in detail by the technical people who had originated or implemented them. Usually, the maintenance philosophy was imposed on the designer; he was told, for instance, that the system was to work as a closed loop. Most presentations present <u>post hoc</u> arguments justifying the design choices and compromises that were made. Among the systems treated are the following:

1. Dynamic accuracy test set
2. IFF system tester
3. BMEWS system checkout
4. Organizational missile test set (Sergeant missile)
5. Terrier-Tartar test equipment
6. MD-7 fire control system test equipment (B-58)
7. Flight control systems test set (B-58)
8. Aircraft and weapon control system test set (F-106)

93. Payne, H. H., ORDVAC Reversing Leapfrog Tests, Ballistic Research Laboratories, Memo No. 841, October, 1955, 22 pp.

This report describes a "leapfrog" test for computer checkout.

94. Rocket, F. A., How Do You Know Your Computer Is Working Right?, IBM Data Systems Division, TN 00.11081.399, November, 1959, 14 pp.

General schemes for performing tests on AND and OR circuits are derived. When AND and OR gates are combined in a network, it may not be possible to sense intermediate points in the network. However, a rigorous test of the network can be made if "(1) each AND circuit is checked for its ability to prevent an output, (2) each OR circuit input is checked for its ability to cause an output, and (3) the system output is checked for the possibility that it may be up when it should be down or down when it should be up."

95. Rocs, D. T., A Revised Diagnosis Routine for Whirlwind I Programs, Massachusetts Institute of Technology, Servo Mechanical Laboratories, Report 7138-R-1 (n.d.), 23 pp.

A computer routine that examines other routines for mistakes is described. At selected points in the program under examination printouts are made of the number of times various operations are performed, the contents of various registers, etc. This allows the programmer to troubleshoot his programs.

96. Rome Air Development Center, Final Report On Study of Fault Location and Prediction Techniques Leading to Plans for Automatic and Dynamic Testing of Military Ground Equipment, RADC-TR 59-248 A&B, February, 1960; two volumes, 186 pp. and 195 pp.

This report examines the design of "test systems having inherently the capability for full performance monitoring and checkout of a whole family of complex systems, and also for prompt diagnosis of both catastrophic and gradual failures whose symptoms may be revealed in the monitoring or checkout process." The practical development of an Automatic Fault Locator (AFL) is discussed.

As to accuracy, an AFL should have "the ability to detect and isolate significant, catastrophic system faults, and in addition the ability to detect (perhaps very indirectly) submarginal circuit or unit

performance, but in implementing the latter capability the accuracy and precision sought will be only that sufficient to give a warning of malfunction to operating or maintenance personnel."

Compromises must be made in the flexibility and degree of thoroughness of AFL performance, because ideal flexibility and thoroughness would require "an instrument of enormous complexity and considerable bulk. The probabilities of failure within the AFL system would at least approximate those of failure within many of the equipments which it would be called up to monitor and check...and...this circumstance would lead to confusion and distrust on the part of personnel concerned with its operation."

An AFL should serve as a "fault locator or failure indicator, rather than as an instrument which spells out exactly what change needs to be made in what component value to restore an equipment to optimum operational status." The equipment should be general enough to handle most electronic signal generation, sensing, and evaluation processes; in particular, the "nerve center" or sequence control should be capable of supplementation by new sensor and transducer techniques without requiring redesign of the master sequencer itself.

The study indicates that a single, general-purpose AFL can cover a broad spectrum of fault location tasks, and that it can serve well either "as a performance monitor at the scene of operations, or (2) as a very useful device for expediting maintenance and repair at a depot." In view of the differences between "on-line" and "off-line" requirements, however, it might be more economical to pursue two lines of AFL development. The on-line AFL system, for example, may demand time-sharing and other arrangements for sampling parameters without distorting on-line performance; these complexities would not be necessary for a shop-model AFL. Also, the depth of fault location might tend toward the module level for on-line AFL and the component or sub-stage level for the shop AFL.

The AFL concept assumes that the equipments under test (EUT) are electrical or electronic; even though the ultimate parameter being measured may be chemical, acoustic, or mechanical, the AFL will transduce the non-electrical data into electrical phenomena. Testing is then performed on the "transfer function" of the separate elements. The transfer function is the mathematical term relating output(s) to input(s) for a given circuit, unit, or system. Since the proper operation of a set of circuit elements depends "directly on whether the transfer functions are within acceptable tolerances, therefore fault detection and isolation is a process of determining whether a known stimulus, when applied at a given point, produces a particular prescribable output response at another given point." The transfer function approach to test and evaluation is believed to reduce the risk of obsolescence, since testing is directed not at physical properties (which might change with new processes) but rather at the acceptability of a response produced by a prescribed excitation.

The equipments for which the AFL is applicable may be grouped into four main categories: (1) communications, (2) data processing, recording, storing, transcribing, and computing, (3) power production, conversion, and distribution, and (4) excitation, control, or monitoring of non-electrical phenomena or processes.

Power equipments are believed to be least challenging to AFL, because of relatively simple circuitry and input-output quantities. In order of increasing difficulty of AFL development, data handling equipments are probably next; many signal paths and circuit elements are usually encountered and sophisticated sequencing is necessary. On the other hand, except for analog computers, many of the parameter states are discrete, repetitive, and not frequency-dependent, features which are favorable to automatic operation. Communication equipments are apt to present a "variety of admittance configurations which the AFL would have to evaluate. Also, both the normal signal inputs and internal driving functions in the Communications group are probably, in general, more complicated time functions than those in any other."

Just because a system is a newly designed, "edge-of-the-art" arrangement does not guarantee that it will have an extremely large number of checks. "The number of significant inputs and outputs of an elaborate surveillance system used in countermeasures procedures would likely be less than that of a relatively simple telephonic switchboard or multiprocess monitoring system." The sheer number of point-to-point transfers to be checked is not a critical AFL limitation. It is true that a large number of transfers necessitates a longer total check time, "but since the AFL system as conceived is capable of very rapid sequencing, it is likely that the recurrence rate for total EUT test will be determined more by the needs of the situation than by any limitation of the AFL."

What if the principal transfer functions are variable functions of such parameters as time, frequency, or operator control action? In these cases, the sensing and excitation are still likely to be straightforward, with the real AFL problem being the analysis of the data from the transducers. On the other hand, for transfer functions where the response must fall within extremely narrow limits, the processing is apt to be easy and the measurement process may be expensive and impractical. For tuned, high-Q circuits, special problems in probe isolation and close frequency control may be encountered.

If the EUT operates full time, the ease of instrumenting an AFL scheme may be contingent on "dead time" in the duty cycle, for it may be only during these brief intervals that signal insertion and sampling can be achieved. It may be necessary for the AFL to sense and evaluate environmental stimuli, if these are closely related to equipment performance.

The algebraic requirements for failure detection are stated: "in general, one set of excitation and response measurements is sufficient to determine unambiguously whether a system parameter is within or out-of-tolerance only if it is possible to establish an equation where the parameter appears as a single unknown." The generalization follows: "a definitive symptom of failure of some element within a module or unit will be revealed, if at all, only in a set of 'n' relationships linking excitations and responses, where 'n' is the number of circuit elements--or more precisely, circuit parameters--within the module or unit."

This "n-variable" logic can be extended to the actual circuit case, and there is a possibility of exciting a module with enough signals to solve for the values of the different components in the module. Logically, then, piece-part fault identification within the module can be accomplished positively by suitable computer programming.

Despite the basic appeal of such computer-controlled schemes, various difficulties are evident. The procedures do not work well with non-linear elements; usually the assumption of linearity must be made for both the normal circuit and the fault condition. Physical isolation of the module itself may be necessary, if the input-output transfer is to be critically examined. The number of unknowns in the module may far exceed the number of parts. "Some significant percentage of faults in any system is traceable not to departure from required value of a given capacitance, resistance, or inductance, but to the fact that (because of) fatigue, vibration, environmental conditions, etc., significant impedances and/or admittances come to exist in the paths that interconnect circuit elements."

For simple systems, it is usually apparent to the operator when failure occurs. With more complex systems, the operator may have no way of knowing whether the system is performing adequately, if certain superficial aspects remain stable. This calls for a fairly continuous over-all system check. Thus, "it would be highly desirable in an automated radar test system to be able, by air link and microwave hour, to introduce into the antenna system a minimal-level simulated target and automatically to detect whether an appropriately coded response appeared at the output of the target-data digitizer." Such over-all checking methods are also naturally adaptable to AFL self-checking, and they will tend to reduce the necessity for detailed checking of operator-varied controls.

Several operational constraints for the AFL concept are mentioned. In the first place, the EUT should not be disturbed in such a way as to impair system performance; this implies reliable interlock provisions and tight coupling between EUT duty cycle and the AFL test regime. A second ground rule is the "avoidance of methods requiring analytical judgment and physical manipulation by operating personnel," presumably in the interest of standardization and efficiency. Third,

tests requiring the EUT to be de-energized should be avoided. (It is recognized that some such checks may be indispensable.)

It is desirable for the sensed test data from all test points to be in the same analog form. Of the many possible ways of expressing the analogs, unipolar voltages are considered to be the most advantageous. Voltages are manageable for machine comparisons; they can be picked up over low impedances, they can be expected to be relatively independent of EUT duty cycle, and they can be easily transmitted from dispersed locations to a central AFL comparator.

Given a unipolar voltage analog as the typical analog test parameter, four main classes of failure tests can be distinguished: Class A, power inputs and outputs; Class B, checking of internally generated control voltages, triggers, gating step-functions, etc.; Class C, input simulation methods; and Class D, environmental testing.

Each class of test has its own problems of AFL implementation. Class A tests will probably be the easiest to implement, and can be expected to provide sufficient diagnostic information for about half of the failures. Class B tests, even though they have no separate excitation, may require complex conversion circuitry. Class C tests will probably be the most difficult to implement because of the precise stimulation signals that must be provided. Some trade-offs between accuracy and coverage can be made; a scheme that tests only 60 per cent of the significant transfer functions but does these with high accuracy may be preferable to a 100 per cent coverage and a higher error rate. Generalizations about Class D or environmental checks are difficult because of the range of situational variables. Equipment performance degradation generally lags environmental conditions; therefore, "Class D tests have fault prediction capabilities; an indication of out-of-tolerance of system-generated environmental conditions is a signal to take corrective action."

A failure might be described by tests of more than one class. An illustration case is a failure in a gated stage of a video amplifier. "A Class B test might reveal this failure in an out-of-tolerance condition with respect to the gating voltage applied to the gating grid in the stage. Likewise, a Class C test might reveal the failure in terms of an out-of-tolerance condition of the primary signal transfer function linking video input to video output."

Processing of the results from these different classes of test would generally proceed in a hierarchical manner. Thus, if a failure caused out-of-tolerance findings for many test points, the machine analysis sequence is to investigate Class A results first, and not to proceed to B and C unless required. In the case where a Class A fault is cleared but Class B and Class C out-of-tolerance indications persist, then the conclusion is that mere than one system transfer function was out-of-tolerance.

Empirical determination of tolerance limits seems to be inescapable if the system to be automated is at all complicated. This is because the transfer functions may have "non-linearities and inexactness which inherently make it very hard to state with assurance in advance just what values of the final form of the converted data correspond to in-tolerance conditions." Provision should be made for competent installation personnel to make on-site adjustments of tolerances.

Test timing will not be difficult for Class A, Class D, and some Class B tests. For many Class B and C tests, however, special sampling and processing provisions must be made. Perhaps the worst case to be encountered is when the signal inputs are random in time and the EUT cannot be shut down for Class C tests. This condition implies sensing circuits that recognize whether a signal is present, as well as a programmed sequence for running tests while no "real" signals are there. Ideally, this test sequence could be interrupted by a sensed signal and still resume the tests later without losing any of the earlier test information. If a simple "holding circuit" were available for holding voltage levels over low impendances, then "integrating Class B and C tests into the overall test program would be nearly as easily accomplished as integrating Class A and Class D tests."

Two basic types of fault-isolating sequences are distinguished. The branching method is a successive-contingency form of analysis; the steps have been carefully programmed in advance. Thus, the programmed series is altered according to the test data obtained, and "closes in" on the trouble. Branching may extend to the initiation of new checks that were not in the basic program. The so-called simple ordering method is more of a coincidence technique. No-go readings at the different test levels (Class A, B, C, and D) are studied, and a pattern of these discrepent readings related to a hypothesized trouble. Preliminary trials suggest that the ordering method may be more effective than a random component model would indicate.

Eight procedures can be followed in designing new equipment to make the system amenable to AFL instrumentation:

1. Use modularization whenever possible
2. Avoid dual functions in the same module
3. Provide space for miniature local transducers and exciters
4. Incorporate high-to-low impedance conversion devices
5. Implement electronic or electrical means for establishing value of system parameters
6. Whenever warning lights, meters, and other indicators are to be designed into the system, provide a voltage analog
7. Require original equipment designers to be aware of the excitation and sensory necessities for Class C tests
8. Devise marginal check parameters

97. Scully, J. F., and L. P. Colangelo, "Field Performance of a New Automatic Fault-Locating Means," Proceedings of the Western Joint Computer Conference, February, 1957, pp. 211-214.

"An automatic fault-locating means has been devised, reduced to practice, and subsequently utilized in a large-scale digital data-processing equipment built for the Rome Air Development Center by the Monroe Calculating Machine Company. The machine solves a classified Air Force problem and contains several thousand logical elements (vacuum tubes and diodes). The Monrobot Automatic Internal Diagnosis (MAID) monitors the machine at all times to make sure that there are no circuit failures which might cause errors in the solution of the problem. Upon occurrence of a failure, the diagnosis unit quickly and automatically localizes the circuit at fault.

"The genesis of this automatic fault-location system lay in the answer to the question: since electronic calculators have been designed to perform automatically operations otherwise handled by humans, why do we not design maintenance machines to replace servicemen? MAID is a pioneer answer to this question."

As to the fault-locating logic, "Self repair implies that maintenance operations are completely mechanized. Five steps are required where maintenance is to be done on electronic calculating or switching circuits: error detection, fault-location, component replacement, error clearing, and restarting. With the exception of component replacement, each step is easily susceptible of mechanization. The system here considered mechanizes these steps and so greatly reduces the time required to repair a fault when it occurs. It does so by scanning points of possible error in the machine. If one point exhibits defective behavior earlier than another, it is regarded as a "better" cause of the error than the other; if, on the other hand, two points exhibit the error simultaneously, that point which is functionally independent of the other is taken as the "better" cause. When all points of the machine have been scanned, one point stands out as the cause of all of the errors which were observed during the scanning process. Phrased alternatively, we may say that of all points of possible error, some subset of points will exhibit the error at the earliest time; of this subset, that point which is functionally least dependent on the others locates the cause. A decimal number assigned to this point appears in lights on the control console; replacement of the plug-in unit associated with this number by a spare completes the repair and permits correct operation to continue."

Operating experience with the MAID indicates that substantial gains were realized over normal troubleshooting techniques, and times were approximately halved.

Other benefits are hypothesized: "The automatic diagnosis means employed has additional advantages not reflected directly in the efficiency figures. One of the most important of these is the

reduction in the level of training required to maintain the equipment. Since the difficult task of locating troubles is now mechanized, most troubles can be serviced by personnel with very little technical skill who could not, without this aid, service the equipment at all. Secondly, as a production trouble-shooting means, impressive reductions in delivery schedules can be made with no increase in technical staff, a matter of great importance in these times of critical shortage. Thirdly, training of personnel to a high degree of efficiency is made much easier, as the machine itself does much of the teaching! Also of great importance is the security inherent in the certain knowledge that an equipment is performing correctly at a given time.

"The application of automatic diagnosis discussed here is the first in the art. We believe that it has fully lived up to expectations, but recognize at the same time that improvement is certainly possible. In the first place, the desirability of extension of the principle to include complete systems, rather than portions only, was clear from the outset. The practical limitations which weighed against doing this in the prototype have since been removed and succeeding calculators have been built with the completely automatic system. The advantages of doing this have been realized in practice. Also, it has been recognized that MAID application should be considered as a vital part of the design of equipment if its full potentialities are to be achieved. Experience has shown that applique construction is often possible, but not as efficient. Again, since the past experience of the people concerned has been largely in the field of digital techniques, it was natural to devote the major application effort in this field; however, it must be stressed that the means are applicable to many nondigital electronic systems. Work is progressing to improve the actual means employed so that both simpler circuitry and even more rapid fault analysis can be made. Consideration has also been given to more direct correlation of trouble indication with defective component to still further simplify the duties of maintenance personnel."

98. Sell, R. P., "Program Debugging for Parallel Processing," paper presented at the National Conference of the Association of Computing Machinery, August 23-26, 1960.

Parallel processing is described: "The Honeywell 800 provides for automatic parallel processing. The term 'automatic' is used here because up to 8 programs may be run on the system, without the use of any monitoring program. The sequencing of these programs is automatic through inclusion of a control memory and special built-in equipment called Multi-Program Control and Traffic Control."

In the design of this debugging system for the Honeywell 800, "two criteria were of overriding importance:

1. The checkout system should be capable of processing any number of programs in a checkout run with a minimum of human intervention and thus with a minimum of idle machine time.

2. The checkout system should not require any changes to a program solely for the purpose of debugging. At the same time, the system should furnish the programmer with enough diagnostic information so that a maximum of errors could be corrected after given checkout run.

"These basic techniques in the Honeywell 800 checkout system are applicable to serial computers just as well as to a multi-program computer. The latter, however, makes highly desirable additional techniques which take account of parallel processing. While self-destructive programs have been with us since the beginning of the computer age, parallel processing introduced the possibility, remote as it may be, of mutually destructive programs. Interference between programs in parallel processing may take one of three forms:

(1) Control branches--as far as the originating program is concerned--into 'wilderness.' If this 'wilderness' is the assigned memory area of a parallel-processed program, unpredictable results may occur.

(2) A program stores or reads information into memory areas occupied by a parallel-processed program. This 'clobbering' of one or more words in another program may not disburb the operation of the originating program but it could, probably would, seriously interfere with the proper operation of the offended program.

(3) A program refers destructively to one or more unique registers in the central processor like Accumulator, Low Order Product Register, Mask Register, or Stopper Address. If the contents of such a register were required in subsequent operations by a parallel-processed program incorrect results could be developed."

99. Stone, K. O., P. Meissner, and K. M. Schwarz, The Expendability of Electronic Assemblies, National Bureau of Standards, NBS Report 6148 (n.d.)

"The optimum module which would lead to lowest overall procurement cost and at the same time be of aid in the solution of logistic and maintenance problems would be one containing from 4 to 8 tubes. This is true for both disposal-at-failure and repairable modules."

100. Tyndall Air Force Base, Evaluation of the UG 897 Automatic Test Set, Project ADC/73AD/59-12, October, 1959.

An evaluation of the UG 897 was conducted by using the set to find inserted and actual malfunctions in the F-101B Automatic Flight Control System (AFCS) and Central Air Data Computer (CADC).

"The UG 897B-1 proved both highly accurate and reliable to an extreme not often found in this type of equipment. During the evaluation, the test set accurately located all induced and actual flight

malfunctions assigned to it. Use of the set reduced average flight line trouble-shoot time by an estimated 80% and, in many cases, eliminated a functional check flight. This represented a considerable savings in manpower, flight time and dollars. The tester has considerable growth potential toward checking other electrical systems and aircraft.

"The UG 897B-1 can replace all existing F-101B AFCS flight line test equipment and do the job faster with greater dependability. With the aid of a suitable pneumatic pressure source, the same statement may be made of its ability to check out the CADC. In its present configuration, however, it can test only the electrical circuitry within the CADC, covering only an estimated 80 to 90 percent of the usual 'flight squawks'."

101. Uchiyamada, H., Comprehensive System of Service Routines, Digital Computer Laboratories, Massachusetts Institute of Technology, December 17, 1952 (revised 1953), 31 pp.

The word "service" refers to the editing, program change, and input/output functions. No reference is made to checkout or maintenance.

102. Williams, C. R., A Review of ORDVAC Operating Experience, Ballistic Research Laboratories, Memo No. 756, January, 1954, 19 pp.

Three kinds of checkout tests are described:

1. A "read-around test" to check memory (this is a requirement peculiar to electrostatic memories where repeated reference to one memory location may influence adjacent locations)

2. Input/output tests

3. "Leap III," an arithmetic, control and memory test

103. Webig, W. H., and L. E. Tryon, Fault Location Study, RADC-TR-59-250, December, 1959, 2 Vols., 149 pp. plus 2 appendixes and 90 pp.

This investigation concerned the feasibility of automatic fault location equipment for two existing SAGE radars (Search RADAR FPS-20 and Height Finder Radar FPS-6), and parallels Item 96.

Only two fault isolation concepts are considered. One is the "simple ordering" idea: go/no-go results are read continuously from the whole collection of test points; to analyze these indications, a fixed routine is programmed and interpretation of the data takes relatively little advantage of redundancies or serial dependencies in the test scheme. This simple ordering method is rejected in favor of logical sequencing or branching. In this latter scheme, the decisions to

make another test and which test to make are contingent upon the results of preceding tests. Thus the program "pursues" the trouble instead of trying to find it by fixed comparisons. In general, signal voltages only are sampled, since supply voltages can be monitored by communtator-comparator methods at the power sources. No-go indications from the commutators could then cause the main fault location program to be inhibited until the supply voltages were at satisfactory levels.

Most branching tests would be either go/no-go or hi/lo/go. A few intrinsically difficult tests were noted (e.g., velocity response shaping characteristics), and problems in setting limits were regarded as "difficult but amenable." Open-loop tests on servomechanisms are regarded as undesirable since performance interruption would usually occur and a decision must be made by operating personnel as to whether or not operation should be interrupted to permit further fault isolation procedures on an open-loop basis.

It would be possible to have a central or master fault locator that could control the subsystem programs from a single storage position. Such an arrangement would save individual comparator programmer units. But it would be accompanied by so many disadvantages (complexity, storage, maintenance, and programming requirements) that the present recommendation is for individual fault locators that can later be converted to a central control arrangement.

The relative merits of parallel and serial comparators are investigated; a direct qualitative parallel is recommended. Implementation of the access speed and volume of program storage requirements are probably within present technological capabilities.

ADDITIONAL REFERENCES

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